

**Characterizing tame oat (*Avena sativa* L.) competitive response to  
wild oat (*Avena fatua* L.) interference**

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## Abstract

The inherent genetic similarity between oat (*Avena sativa* L.) and wild oat (*Avena fatua* L.) precludes selective herbicide use to control wild oat. Consequently, large reductions in oat yield and quality due to wild oat consistently constrain oat production in western Canada. Traditionally, delayed seeding followed by tillage prior to planting was used to control wild oat, but new studies have shown that this practice also results in substantial reductions to oat yield and quality. Thus, new methods are needed to ameliorate the adverse effects of wild oat competition on oat. Planting more competitive varieties with earlier emergence and larger seeds may minimize losses associated with wild oat competition. Therefore, the objectives of this research were i) to determine the influence of wild oat emerging at different times and varying densities on oat yield and quality and ii) to determine the relative importance of seed size and genotype in affecting wild oat – oat competition. High densities of early emerging wild oat greatly reduced oat yield and increased wild oat contamination. Observed oat yield losses were as great as 70% and resulted in a 15% wild oat contamination level. Wild oat that emerged before oat also had higher biomass and reproductive output than wild oat that emerged after oat. Furthermore, early emerging wild oat reduced percentage plump oat kernels and increased percentage thin kernels. Oat plants established from large caryopses produced 18% more biomass and 15% more panicles  $\text{m}^{-2}$  than plants established from small caryopses. In addition, wild oat produced 31% less biomass and fewer panicles  $\text{m}^{-2}$  when grown with oat plants established from large caryopses. CDC Boyer appeared to be the most competitive of the varieties examined, having significantly higher biomass and panicle production both in the presence and absence of wild oat competition. Conclusions that emerge from this research are i) emergence time is critical to wild oat – oat competition, ii) it is essential for oat producers to control early emerging wild oat and ensure crop emergence precedes wild oat emergence, iii) planting large seed of competitive cultivars may improve the competitive response of oat to wild oat.

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## **List of Abbreviations**

AC	Agriculture and Agri-Food Canada
ANOVA	Analysis of variance
CDC	Crop Development Center
ET	Emergence time
G	Genotype
GDD	Growing degree days
IH	Indian Head Research Farm
KCRF	Kernen Crop Research Farm
R	Run
REML	Restricted maximum likelihood
S	Caryopsis size
SY	Site-year
TKW	Thousand kernel weight
WD	Wild oat density
WO	Wild oat

## 1.0 Introduction

Oat (*Avena sativa* L.) is one of the earliest domesticated crops grown for human consumption, having been widely utilized as both a grain and forage crop in Western Europe as early as 1000 A.D. (McMullen, 2000). Widespread cultivation of oat originally occurred upon recognition of its nutritional properties (Burnette et al., 1992). More recently, expanding recognition of the nutritional value of the oat grain coupled with increased health consciousness of consumers has resulted in increased oat demand. In the past three decades, the annual acreage seeded to oat in western Canada has increased considerably (Statistics Canada, 2004), with much of this attributed to improved yields, grain quality, disease resistance and market demand.

One of the primary concerns associated with oat cultivation is competition with wild oat. Since its introduction into western Canada by the early settlers, wild oat has become widely dispersed and caused considerable losses in numerous crops. Nalewaja (1977) estimated that annual wheat and barley yield losses in North America due to wild oat exceed 6.4 million tonnes. If allowed to compete throughout the entire growing season, wild oat densities of 64 and 118 plants  $\text{m}^{-2}$  reduced wheat grain yields by 28% and 39%, respectively, compared to when removal occurred at the 1-leaf stage (Kirkland, 1993a). Barley yield losses ranged from 30-50% in Australia when wild oat densities exceeded 100 plants  $\text{m}^{-2}$  (Chancellor and Peters, 1974). Likewise, in France, a density of 48 wild oat plants  $\text{m}^{-2}$  caused a 17% reduction in barley yield (Gournay, 1964).

A variety of chemical and mechanical control measures have been implemented to control wild oat in several crops with varying degrees of success (Banting, 1970; Friesen and Bowren, 1973; Banting, 1974). However, due to the genetic similarity between *Avena sativa* and *Avena fatua*, no herbicides exist to selectively control wild oat in oat. Oat producers are thus forced to manage wild oat using cultural control methods, but the

degree of control with these methods is frequently inadequate. Planting more competitive oat varieties may be one way to improve the ability of oat to compete with wild oat. However, despite successful breeding efforts aimed at improved quality, yield and disease resistance, little work has been conducted to develop more competitive varieties.

A key attribute of more competitive varieties may be early emergence. Several studies have shown that the relative time of emergence of wild oat and the crop may influence its competitive ability (Thurston, 1962; McBeath et al., 1970; Chancellor and Peters, 1974; Peters and Wilson, 1983; O'Donovan et al., 1985; Peters, 1985). Planting larger caryopses of more competitive varieties may be another method to improve the competitive response of oat to wild oat interference (Kiesselbach, 1924; Demirlicakmak et al., 1963). In wheat, planting large seeds reduced yield loss due to wild oat more than did increased wheat seeding rate (Stougaard and Xue, 2004). Little is currently known about the influence of wild oat relative time of emergence and density on oat yield and quality, and the effect of caryopsis size on oat competition with wild oat has not been examined.

The focus of this project was to evaluate methods to improve oat competitive response, or the ability of the crop to avoid suppression by wild oat competition. In addition, the research was to determine the role of wild oat time of emergence and density in affecting competition between the two species. The primary hypothesis was that oat would be more competitive with wild oat when established from large caryopses, and when wild oat emergence followed oat emergence. The following key questions were addressed:

- (1) What are the reductions in oat yield and quality when wild oat emerges before compared with after crop emergence?
- (2) What effect does wild oat relative time of emergence have on wild oat growth and fecundity, and how is this influenced by density?
- (3) Can planting large oat caryopses improve the competitive ability of oat versus wild oat?
- (4) Are caryopsis size effects genotype-dependent?

Answers to these questions will provide information to develop recommendations for producers, agronomists, and breeders to minimize oat losses due to wild oat. Questions one and two will provide breeders with an estimation of the value of using emergence time as a selection criteria in breeding programs. Furthermore, questions one and two will provide a quantification of oat yield and quality losses, as well as wild oat seed production and contamination over a range of wild oat emergence times and densities. This information will not only be valuable to producers and agronomists, but will be important in the development of bioeconomic, decision rules-based models. The potential of oat genotypes to minimize yield loss and even reduce wild oat growth with increasing caryopsis size is addressed in questions three and four. These results should contribute to a more integrated approach to managing wild oat in oat.

## **2.0 Literature Review**

### **2.1 Crop-weed competition**

#### **2.1.1 The competitiveness of wild oat**

Wild oat (*Avena fatua* L.), an annual grassy weed that infests small-grain crops, is one of the most economically detrimental weeds of cultivated land worldwide (Holm et al., 1977). Because of its adaptability to a broad range of climates and environments, as well as its intense competitive nature, wild oat is regarded as one of the 12 most successful colonizing species globally (Allard, 1965). The negative outcome of wild oat competition on crop yield and profitability is extensive, with annual losses across the Prairie Provinces estimated at \$500 million (Manitoba Agriculture, 2001). Despite large efforts to control the weed through herbicide use and various technological advancements, wild oat populations continue to persist, and it remains one of the most abundant and competitive weeds on the Canadian Prairies (Kirkland, 1993a; O'Donovan et al., 2000). Not surprisingly, wild oat was found to persist on approximately 51% of fields surveyed in Saskatchewan in 2003 (Leeson et al., 2003).

The relative success of any plant in its environment is a function of its ability to obtain sufficient resources for growth (Saghir et al., 1968). Individual plants make demands on a common pool of resources that are spatially or temporally limited (Booth et al., 2003). Therefore, competition may be defined as, “the mutually adverse effects of plants that use a resource in short supply” (Barbour et al., 1980), and essentially results in certain plants obtaining insufficient resources for growth. Consequently, one or both of the competing species will exhibit reduced yield (biomass, grain, or both).

Two types of plant competition occur in nature: intraspecific and interspecific. Intraspecific interactions occur between individuals of the same species while interspecific interactions involve individuals of different species. Weeds such as wild oat reduce crop yields by competing for resources such as nutrients, light, moisture, and space (Kirkland, 1993b). Thus, the presence of weed species in a crop exhibits certain negative effects on the crop, an interaction termed interference (Radosevich et al., 1997).

Considerable research has been conducted to examine the effects of wild oat interference on crop yield (Gournay, 1964; Dew, 1972; Nalewaja, 1977; O'Donovan et al., 1985; Evans et al., 1991; Kirkland, 1993a; O'Donovan et al., 1999). Losses caused by wild oat competition vary greatly with crop species and geographical location. Barley yield loss ranged from 30-50% in Australia when wild oat densities exceeded 100 plants  $\text{m}^{-2}$  (Chancellor and Peters, 1974). In Idaho, barley yield losses exceeded 40% from a wild oat density of 170 plants  $\text{m}^{-2}$  (Morishita and Thill, 1988). In Canada, 150 wild oat plants  $\text{m}^{-2}$  emerging 6 days before the crop reduced barley yield by 42% (O'Donovan et al., 1985). Similarly, Friesen (1960) reported that in Canada, a density of 113 wild oat plants  $\text{m}^{-2}$  reduced wheat yields by 77.5% compared to plots with only 12 wild oat plants  $\text{m}^{-2}$ . Martin et al. (1987) observed yield losses as great as 78% in wheat (*Triticum aestivum* L.), while Kirkland (1993a) reported losses of 28% when wild oat competed with wheat throughout the entire growing season.

### **2.1.2 Competitive responses of crops to weed interference**

Crop interference in weed growth and reproduction is an essential method of weed control in numerous cropping systems (Jordan, 1993). Concerns about herbicide safety have resulted in an increasing reluctance to use chemical weed control and consequently, have revived interest in crop interference as a weed control method. In addition, chemical control of many weed species in some crops is lacking, as is the case for wild oat in oat. Likewise, red rice (*Oriza sativa* L.) herbicide control in cultivated rice (*Oriza sativa* L.) is lacking due to the genetic similarity between the species. Red rice produces more tillers, is generally taller than cultivated rice, and is consequently more competitive



than cultivated rice (Diarra et al., 1985). As such, red rice consistently reduces cultivated rice yield and quality (Smith, 1988). Competition between rice and red rice has been reported to be highly dependent on red rice biotype, density, and emergence time (Smith, 1988). In these situations, the use of crop interference and cultural control methods becomes imperative for successful weed management. For example, the use of competitive rice cultivars known to interfere with red rice growth has reduced yield losses associated with red rice competition (Diarra et al., 1985; Kwon et al., 1991).

Crops generally respond to weed interference in three ways: a competitive effect, a competitive response, or a combination of both (Callaway, 1992). In some instances, crops can suppress weed growth and reproduction, termed a competitive effect (Goldberg and Landa, 1991). In other situations, the crop is able to avoid suppression by weed interference, termed a competitive response. Genotypic diversity and the resulting variation frequently lead to a competitive effect. For example, Wicks et al. (1986) observed that among 20 winter wheat varieties, the most suppressive variety allowed 82% less weed biomass production than the least suppressive variety – a competitive effect. Alternatively, ‘HD-2009’ winter wheat demonstrated a yield loss due to wild oat of 60% compared with a 27% yield loss in ‘HD22-85’ (Balyan et al., 1991), illustrating a competitive response to weed interference. Fortunately, the two are frequently correlated and are collectively referred to as the ‘competitive ability’ of the crop (Mohler, 2001a). The degree to which these correlations exist among cultivars is, however, largely a product of genotype by environment interaction. Nevertheless, the differential ability of varieties to suppress weed growth affords producers the opportunity to exploit crop interference as a potential component of integrated weed management systems.

## **2.2 Factors influencing crop-weed competition**

Weeds reduce crop growth, yield, and quality when allowed to interfere with crop development (Radosevich et al., 1997). The magnitude of these reductions hinges on the competitive abilities of the competing species. A species’ competitive ability is determined by a number of factors including time of emergence, relative growth rate, and

density, all of which influence the ability of the species to obtain the limiting resources that are essential for growth and development (Harper, 1977). The outcome of crop-weed competition then, is determined by several criteria and their ability to act additively or multiplicatively on plant growth and hence, interference.

### **2.2.1 Relative growth rate and early growth characteristics**

Grime (1977) characterized weeds as plants that possess physiological, morphological, genetic, and ontogenetic traits for rapid growth. Species that grow faster or larger than their neighbours will ultimately take up more available resources (Roush and Radosevich, 1985). Greater plant size is believed to confer increased competitive ability (Harper, 1977). Thus, relative growth rates (RGR) frequently reflect plant competitive abilities. Two types of growth rates can be used to describe weed growth: absolute growth rate is the accumulation of biomass per unit time ( $\text{g day}^{-1}$ ), whereas relative growth rate is the accumulation of biomass per unit initial biomass per unit time ( $\text{g g}^{-1} \text{day}^{-1}$ ). Because agricultural weeds have the highest RGR of any large category of plants (Grime and Hunt, 1975), they are serious competitors in numerous ecosystems. However, they are arguably most problematic in the agroecosystem.

Comparing the RGR of crops relative to weeds is essential from a weed management perspective. In both weeds and crops, RGR declines as plant size increases (Grime and Hunt, 1975). Likewise, RGR is also believed to decline as seed size increases, with large-seeded weeds such as cocklebur (*Xanthium strumarium* L.) tending to have a RGR similar to that of many crop species (Seibert and Pearce, 1993). Although the large initial seed size of crops gives them a lower RGR than many weeds, their larger mass usually provides a greater leaf area and root system at emergence, rendering them competitively advantageous over smaller-seeded weeds (Mohler, 2001b). Large seeds tend to produce larger seedlings that give rise to larger plants and thus, lower RGRs.

RGR is also highly correlated with leaf area ratio (LAR), the amount of leaf area per unit of total plant biomass (Radosevich et al., 1997). In *X. strumarium*, higher RGR in the small-seeded plants was primarily due to a higher LAR (Seibert and Pearce, 1993).

Because the photosynthetic rate of a plant is a product of leaf area and the incident light upon that leaf area (Cudney et al., 1991), LAR should be a strong determinant of RGR. Therefore, factors such as plant density that alter leaf area, canopy structure, or light penetration should also affect growth rate. Wild oat densities ranging from 100 to 300 plants m<sup>-2</sup> reduced the leaf area of wheat at early growth stages and low densities (Cudney et al., 1991). This resulted in reduced light penetration at later growth stages and high wild oat densities, ultimately reducing wheat growth rates and competitive ability. *Trifolium subterraneum* L. (subterranean clover) had a higher RGR than *Trifolium incarnatum* L. (crimson clover) and *Trifolium hirtum* L. (rose clover) when grown in mixtures, but a lower RGR than when it was grown in monoculture (Williams, 1963).

Relative growth rates of both weeds and crop are dependent on a number of factors as described above. Nonetheless, the RGR of weeds and crops plays an important role in determining the outcome of competition and more specifically, crop yield. However, RGR represents one small factor affecting competition and its effects are usually outweighed by relative time of emergence and density of the weed and crop, both of which serve to influence RGR.

### **2.2.2 Relative time of emergence of weed and crop**

The timing of weed emergence relative to crop emergence has a fundamental influence on crop growth and yield. A number of factors influence seedling emergence time including seed size, dormancy, germination, moisture content, temperature, and the interactions between these (Peters, 1982; Lafond and Baker, 1986a,b; Hampson and Simpson, 1990; Jurado and Westoby, 1992). Weed seedling emergence time is important because it generally determines how competitive a plant will be with its neighbours (Forcella et al., 2000). For example, a crop that emerges after a weed will be at a competitive disadvantage because competition for resources is often asymmetric. Earlier emerging plants are able to accumulate resources earlier and thus become larger. Moreover, large plants are generally believed to have greater competitive ability than

smaller plants (Harper, 1977). It becomes essential then, that the outcome of weed-crop competition be quantified as early as possible in order to provide timely weed control (Knezevic et al., 1995).

Although the importance of weed emergence time relative to the crop in determining the magnitude of crop yield loss has long been recognized, the development of integrated weed management (IWM) systems has recently renewed interest in this research area. Because IWM emphasizes the use of multiple weed management strategies, including chemical, cultural, mechanical, and biological methods (Swanton and Weise, 1991), a greater understanding of the ecology and biology of weed species are necessary. Furthermore, concerns about pesticide safety have initiated an effort toward reduced chemical weed control. In response, bioeconomic yield models have been developed to reduce herbicide use by recommending herbicide application only when weed densities and estimated crop yield loss warrant their use (Jasieniek et al., 1999). Decision rules in these models are based on weed economic threshold densities, which are a function of crop and weed density and time of emergence, and are calculated using crop yield loss. Therefore, much research has been devoted to describing the relationship between weed time of emergence and crop yield loss (O'Donovan et al., 1985; Martin and Field, 1988; Dieleman et al., 1995; Knezevic et al., 1995; Bosnic and Swanton, 1997; Conley et al., 2003).

Weeds emerging before the crop cause greater yield loss (O'Donovan et al., 1985; Dieleman et al., 1995; Knezevic et al., 1995; Bosnic and Swanton, 1997), produce more seed (Peters and Wilson, 1983; Bosnic and Swanton, 1997), and have higher shoots weights and competitive indices (Martin and Field, 1988) than weeds that emerge subsequent to the crop. At similar weed densities, yield losses ranged from 22 to 36% when barnyardgrass (*Echinochloa crus-galli* L.) emerged before corn (*Zea mays* L.) compared to only 6% when emergence followed corn (Bosnic and Swanton, 1997). Reproductive output of barnyardgrass was 14- to 18-fold higher from earlier emerging seedlings than in seedlings whose emergence followed the corn crop. Likewise, pigweed (*Amaranthus* spp.) emerging at the same time as soybean (*Glycine max* (L.) Merr.) at 2 plants per meter reduced yields by 12% compared to a reduction of only 2% when

pigweed emerged at the cotyledonary stage of soybean (Dieleman et al., 1995). Under controlled environmental conditions, wild oat emerging at the same time as spring wheat (*Triticum aestivum* L.) had higher shoot weights and seed production than wild oat emerging 3 or 6 weeks after wheat (Martin and Field, 1988). Several authors have even suggested that time of emergence of a weed relative to a crop is more important than density in determining the impact of a specific weed on crop yield (Knezevic et al., 1994; Chikoye and Swanton, 1995; Dieleman et al., 1995; Bosnic and Swanton, 1997). In fact, for every day that wild oat emerged before wheat and barley (*Hordeum vulgare* L.), crop yield loss increased by approximately 3% (O'Donovan et al., 1985). Clearly, time of emergence of a weed relative to the crop is of considerable importance in cropping systems.

An increased understanding of weed seedling time of emergence, density, and their interaction has many practical applications in weed control, including determination of the critical period for weed control (CPWC). The CPWC can be defined as “the time interval when it is essential to maintain a weed-free environment to prevent crop yield loss” (Swanton and Weise, 1991). This time interval is largely dependent on weed density as well as the time of emergence of the weed relative to the crop (Knezevic et al., 2002). It is likely that large differences in the CPWC within the same crop would be observed when the crop emerged before weeds than when weeds emerged before the crop.

Emergence patterns of the competing weed species as well as their seedbank dynamics are both important in determining the CPWC (Martin et al., 2001). Many weed species exhibit dormancy characteristics and as a result, display variable emergence patterns. Time of weed emergence becomes even more critical when weeds seeds possess varying levels of dormancy, such as in wild oat, which ultimately gives rise to multiple cohorts of varying densities (Thurston, 1966). Thus, quantification of seedling emergence time and periodicity are both key to predicting weed seedling emergence and successful weed management. To this end, several models have been developed to predict seed germination and emergence, the most recent of which is the hydrothermal time model (Bradford, 2002). Despite the high degree of accuracy with which these models can

predict weed seed germination, weeds continue to emerge inconsistently and unpredictably, resulting in crop yield losses of varying magnitude.

### **2.2.3 Weed density and the influence of neighbours**

Plants are sessile organisms and are thus limited in the amount of space they can physically occupy. The quantity and availability of resources essential for plant growth are also spatially and temporally limited. The presence of neighbouring plants thereby induces adversity due to shortages of resources such as light, water, and nutrients, while the density of neighbouring plants determines the intensity of competition for these resources (Trenbath and Harper, 1973; Harper, 1977). Density in this sense is referred to as the spacing of neighbouring individual plants within a local population. Plants respond to the proximity of neighbouring plants with plastic morphological and physiological changes (Ballaré et al., 1994). Specific plant response to density varies among species, but is generally a function of size, shape, and pattern of growth, as well as emergence time relative to other plants (Silvertown and Charlesworth, 2001).

Wild oat density can have a considerable impact on crop-weed interactions mainly through competition for nutrients and water. Because of its competitive nature, wild oat has caused appreciable yield losses even at low densities. Thirty-eight wild oat plants  $\text{m}^{-2}$  reduced wheat yields by as much as 63% at some locations in California (Carlson and Hill, 1985). Friesen (1960) reported that a density of 113 wild oat plants  $\text{m}^{-2}$  reduced wheat yields 78% compared to plots with only 12 wild oat plants  $\text{m}^{-2}$ . However, density increases to higher levels cause relatively small yield reductions due to the asymptotic relationship between yield and density (Silvertown and Charlesworth, 2001). For example, a 30% yield reduction in an Australian wheat crop was observed at a wild oat density of 120 plants  $\text{m}^{-2}$ , and doubling the density resulted in a yield loss of 45% (Paterson, 1969). Although barley is generally believed to be more competitive than wheat, wild oat densities of 192 and 306 plants  $\text{m}^{-2}$  reduced barley yields by 26 and 32%, respectively (Bell and Nalewaja, 1968; Chancellor and Peters, 1974). Despite the large

body of literature regarding the effects of wild oat density on crop yield, a quantification of oat yield loss in response to wild oat density does not exist.

Plant density also strongly influences competition for light. Both light quantity [Photosynthetic Photon Flux Density (PPFD)] and light quality [ratio of red (R) to far-red (FR) light] are modified by plant canopies (Ballaré et al., 1994). As light descends through a plant canopy, R light is absorbed and FR is transmitted and thus, the area under a canopy becomes enriched in FR light. Increasing density increases the FR:R ratio and decreases the PPFD that plants are exposed to. By perceiving these changes in the FR:R ratio, plants can effectively detect the presence of neighbours before being shaded (Smith et al., 1990). Many plants, especially weeds, have developed morphological and physiological responses to shading, termed the shade avoidance syndrome (Smith and Whitelam, 1997). In redroot pigweed (*Amaranthus retroflexus* L.)/corn competition studies, the change in light quality with increasing corn densities resulted in profound differences in pigweed plant height (McLachlan et al., 1993). In a subsequent experiment, redroot pigweed exhibited delayed and reduced reproductive output as a result of decreased transmitted PPFD with increasing corn density (McLachlan et al., 1995). Wild oat is a plant of tall stature that commonly overshadows the crop species in which it is present and therefore may compete more successfully for light than its neighbours. Wild oat leaves also have been shown to have greater longevity and higher LAI in the upper canopy than wheat leaves and consequently, were predicted to intercept more light (Barnes et al., 1990). However, no study has examined either the response of wild oat to light quality or quantity.

### **2.3 The use of models to estimate crop yield loss as a function of weed populations**

Weed interference in crop growth can lead to substantial declines in crop yield and large weed seedbank inputs. As a result, predictive models of weed growth, population dynamics, and crop-weed relationships have received considerable attention in recent years (Cousens and Mortimer, 1995). In agricultural systems, the principles of integrated

weed management dictate that weeds only be controlled when present at densities that would cause economic losses (Swanton and Weise, 1991). Therefore, a large effort to quantify the impacts of weeds on crops has been undertaken in an effort to establish weed density thresholds as a basis for management decisions (Cousens et al., 1987; Dieleman et al., 1995; Lindquist et al., 1996; Jasieniuk et al., 2001). Many of the management decisions made currently rely on the use of bioeconomic yield models designed to make cost-effective decisions for producers based on a number of variables. However, the success of these models is a function of the precision by which the impact of weed populations on crop yield can be accurately predicted (Jasieniuk et al., 2001). Thus, crop yield or yield loss-weed density relationships and the predictive models that attempt to describe them are critical to both weed science and agricultural systems.

Empirical and ecophysiological models of crop weed interference have been used to estimate the influence of weeds on crop yield (Cousens, 1985; Cousens et al., 1987; Kropff and Spitters, 1991; Kropff et al., 1992). Initially, weed density was used in empirical models to predict yield loss from weed interference (Dew, 1972; Cousens, 1985). Most attempts used rectangular hyperbolic functions and reciprocal yield equations modeling yield as a function of density (e.g. Watkinson, 1981; Weiner 1982), but these equations were somewhat complex, often involving the estimation of several parameters. A two parameter rectangular hyperbolic function for estimating crop yield loss developed by Cousens (1985) provided a model with meaningful biological parameters, logical predictions, and simplicity, where:

$$Y_L = \frac{ID}{1 + ID / A} \quad [2.1]$$

where  $Y_L$  is percent yield loss,  $D$  is weed density (plants  $m^{-2}$ ), and  $I$  and  $A$ , are model parameters. Parameter  $I$  is the percent yield loss per unit weed as  $D \rightarrow 0$ , and  $A$  is the asymptotic yield loss as  $D \rightarrow \infty$ . The model assumes that the addition of weeds at low densities causes greater yield loss than the addition of weeds at higher densities, and that yield loss approaches an asymptote at high densities. That is, crop yield becomes constant above some threshold weed density as a result of limited resources (Silvertown and Charlesworth, 2001). Because the rectangular hyperbolic equation was theoretically simple and generally provided good descriptions of crop yield loss data, it was frequently



employed in crop-weed interference studies. Weed density is relatively easy to measure on a small scale, but the model accounts for neither the size of the weed relative to the crop (relative time of emergence), nor variability in the density of the crop. It assumes that the density of one species (the weed) varies while the density of the other species (the crop) remains constant. It is well known, however, that crop density varies considerably among years and fields (Jasieniuk et al., 1999; Jasieniuk et al., 2001).

O'Donovan et al. (1985) suggested that the influence of weed emergence time on crop yield loss was linear, proposing the following simple multiple-regression equation to describe the relationship between density and time of emergence of wild oat, and yield loss in wheat and barley:

$$y = b_0 + b_1 X_1 + b_2 \sqrt{X_2} \quad [2.2]$$

where  $b_0$  is the y intercept,  $b_1$  is the regression coefficient for relative time of wild oat emergence (days), and  $b_2$  is the regression coefficient for wild oat density (plants  $m^{-2}$ ). Several problems with the model have been acknowledged by Cousens et al. (1987), mainly on the grounds that it provides nonsensical predictions when extrapolating outside the range of densities studied. The model also predicts that there can be an increase or decrease in yield depending on emergence time even when no weeds are present which is clearly unreasonable. Furthermore, crop yield and thus yield loss (since the two are interchangeable) are likely constant at high densities in accordance with the law of constant final yield. Although it is not biologically implausible to have yield loss exhibit a linear increase with weed density, it is more realistic to assume that the relationship is asymptotic and thus, the multiple-regression model over-estimates yield loss at high weed densities and underestimates it at low densities.

An alternative is to assume that yield loss is asymptotic above some threshold weed density, that the addition of the first few weeds causes the highest yield loss, and yield loss caused by the first few weeds declines exponentially with increasing (or later) emergence times relative to the crop (Cousens et al., 1987). From this, the following equation can be built upon the rectangular hyperbolic yield loss function described previously by Cousens (1985):

$$Y_L = \frac{ID}{e^{CT} + ID/A} \quad [2.3]$$

where  $Y_L$  is percent yield loss,  $D$  is weed density (plants  $m^{-2}$ ),  $T$  is the relative time of emergence of weed and crop, and  $I$ ,  $A$ , and  $C$  are model parameters. Parameter  $I$  is the percent yield loss per unit weed as  $D \rightarrow 0$  at  $T = 0$ ,  $A$  is the asymptotic yield loss as  $D \rightarrow \infty$ , and  $C$  is the rate at which  $I$  declines exponentially as  $T$  becomes larger. The model provided a marginally better description of O'Donovan et al.'s (1985) data but avoids many of the erroneous properties associated with the multiple-regression model (Cousens et al., 1987). The model has since provided a good description of yield loss in soybean (*Glycine max* (L.) Merr.) (Dieleman et al., 1995; Conley et al., 2003), corn (*Zea mays* L.) (Knezevic et al., 1995), and white bean (*Phaseolus vulgaris* L.) (Chikoye and Swanton, 1995).

To address the problem of weed emergence occurring in successive flushes and the resulting inability of empirical models to adequately account for the effect of relative time of emergence, another approach to quantify weed competition was introduced by Kropff and Spitters (1991). This model was an ecophysiological model:

$$Y_L = \frac{qL_w}{1 + (q-1)L_w} \quad [2.4]$$

where  $Y_L$  is percent yield loss,  $L_w$  is relative leaf area of the weed, and  $q$  is a model parameter representing the relative damage coefficient of the weed on the crop. The model characterizes weed density and relative time of weed emergence by quantifying relative leaf area, and was reported to be a better predictor of crop yield loss than density (Kropff and Spitters, 1991). In addition, only one measurement of relative leaf area is needed to estimate crop yield loss based on relative time of emergence. However, the practical application of this model is limited by the inability to estimate leaf area index quickly and accurately (Knezevic et al., 1995). Furthermore, the relative damage coefficient, or  $q$ , has been found to be spatially and temporally variable in a number of studies (Chikoye and Swanton, 1995; Dieleman et al., 1995; Knezevic et al., 1995; Lotz et al., 1996), compromising model stability and applicability.

The previously mentioned models assume that crop density is fixed while weed density varies and are thus unable to make valid predictions among years or locations in which crop density is variable. Ultimately, the quality of recommendations made by bioeconomic models is critically affected by the yield loss-weed density relationship and its fit to the empirical data (Swinton and Lyford, 1996). Therefore, crop grain yield as a function of weed and crop density was best estimated with the following function (Jasieniuk et al., 2001):

$$Y = \frac{jD_c}{1 + jD_c / Y_{\max}} \cdot \left( 1 - \frac{iD_w}{1 + iD_w / a} \right) \quad [2.5]$$

where  $Y$  is crop yield,  $D_c$  is crop density,  $D_w$  is weed density,  $Y_{\max}$  is maximum crop yield, and  $i$ ,  $j$ , and  $a$  are estimated parameters. The model provided an accurate fit to the winter wheat-jointed goatgrass interference data and thus an increase from two (Cousen's, 1985) to three parameters appears justified (Jasieniuk et al., 2001). However, the model does not incorporate time of emergence, which has been shown to be more important than weed density in other studies (Dieleman et al., 1995; Bosnic and Swanton, 1997). A model that could incorporate all three variables, weed density, crop density, and relative time of emergence, would likely explain a substantial proportion of variation in crop yield.

At present, such a model has not been developed, although Jasieniuk et al. (2001) suggest that the previous model could be adapted to include time of emergence. However, the data set required for accurate estimates of this model would be large and logistically unmanageable. In addition, the development of such a model would likely add another parameter, meaning the resulting equation would involve the estimation of four parameters; one needs to be concerned with overparameterization in such a case as models may require more parameters than is required. Although the development of an “all-inclusive” model as described above is desirable, attention needs to be paid to the instability of parameter estimates in current models at both the temporal and spatial scales. Ultimately, the stability of parameter estimates is imperative to the development successful bioeconomic models with the ability to make accurate predictions (Lindquist et al., 1996).

## **2.4 Enhancing the competitive ability of the crop**

The advent of pesticide-free and organic production systems, as well as growing interest in reduced herbicide use, has led to cultural weed control practices receiving much attention in recent years. Consequently, much importance has been placed on enhancing the competitive ability of the crop. The ability of a crop to compete with weeds is dependent upon a number of cultural practices including the choice of cultivar, planting density and date, as well as initial crop seed size (Mohler, 2001a). Alternatively, these factors also interact to influence weed vigor and competitive ability. Any practice that provides uniform, vigorous crop growth, thereby allowing the crop to interfere with weed growth, should provide some measure of weed control (Jordan, 1993; Radosevich et al., 1997). Appropriately used, crop interference should represent a fundamental component of integrated weed management in any agricultural system.

### **2.4.1 Crop density**

Numerous studies have demonstrated reductions in weed growth and fecundity with increasing crop densities (Radford et al., 1980; Martin et al., 1987; Kirkland, 1993b; Sodi and Dhaliwal, 1998; O'Donovan et al., 1999; O'Donovan et al., 2000). The objective in increasing crop density is to maximize the rate at which the crop occupies space early in the growing season, minimizing competitive weed pressure (Mohler, 2001a). Weed yields generally decline hyperbolically with increasing crop density. At low crop densities weed yield declines at a linear rate until at some threshold crop density weed yield cannot be suppressed further due to limited resources. However, the degree to which the crop is able to suppress weed growth depends not only on the nature of the crop, but also on the biology of the weed.

Several studies have demonstrated that increasing crop density improves crop competitive ability and ameliorates the effect of wild oat on the crop. O'Donovan et al. (2000) observed as much as 10% lower barley yield loss due to wild oat when barley was

seeded at 200 kg ha<sup>-1</sup> compared with 85 kg ha<sup>-1</sup>. Likewise, Sodhi and Dhaliwal (1998) demonstrated that increasing wheat seeding rate from 150 to 200 kg ha<sup>-1</sup> increased its dry matter production through a higher leaf area index and increased light interception. These seeding rates also increased weed suppression ability and concomitantly reduced wild oat dry matter production by 6 and 8%, respectively. Increased crop stand densities also correspond to decreased wild oat seed rain. Increasing barley plant density from 135 to 425 plants m<sup>-2</sup> reduced wild oat seed rain by almost 70% (Evans et al., 1991). Wild oat seed rain was nearly 50% lower when wheat density was 351 plants m<sup>-2</sup> compared to 42 plants m<sup>-2</sup> (Radford et al., 1980). Wheat and barley are generally believed to be more competitive than wild oat and accordingly, have demonstrated large potential to reduce the negative effects of wild oat (Evans et al., 1991).

Increased seeding rates result in increased intraspecific competition and therefore, the relationship between crop density and crop yield can be either asymptotic or parabolic (Willey and Heath, 1969). As density increases, crop yield either approaches a maximum (asymptotic) or approaches a maximum and declines slightly with increasing density (parabolic). For example, Evans et al. (1991) noted that barley grain yield generally increased as barley density increased except at the highest barley density of 415 plants m<sup>-2</sup>. At high wild oat densities, 252 wheat plants m<sup>-2</sup> did not produce significantly higher yields than 117 plants m<sup>-2</sup> (Radford et al., 1980). Although reductions in weed yield and seed rain are achievable at high densities, the fact that crop yield may not increase at high densities may not justify increased seeding rates from an economic perspective. Determination of optimal plant density, the density at which a further increment in seed costs is worth more than the expected increase in yield, is important when using plant density as a means of weed control. Unfortunately, optimal densities for weed suppression in many crops, such as oat, are currently unknown.

#### **2.4.2 Crop genotype**

One low cost cultural weed control option and a key component of integrated weed management systems is to grow competitive crop varieties (Lemerle et al., 2001). The

ability of crops to compete with weeds is largely determined by a strong genetic component (Doll, 1997). Nonetheless, varietal differences in competitive ability among a number of crops have been reported, and it may be possible to breed crops with the capacity to suppress weeds, or with tolerance to being suppressed (Didon, 2002). However, in order to select more competitive cultivars, the morphological and physiological attributes contributing to competitive ability must first be determined (Froud-Williams, 1997; Lemerle et al., 2001).

Crop cultivars with early emergence and vigorous early growth should compete better with weeds (Berkowitz, 1988). Early emergence frequently results in plants of taller stature, as well as early ground cover leading to improved light interception (Richards and Whytock, 1993; O'Donovan et al., 2000). For example, wild oat shoot weight was reduced more by a tall barley cultivar with early emergence than by a shorter cultivar (O'Donovan et al., 2000). In addition, cultivars with poor emergence (cv. Falcon and CDC Dawn) had the highest wild oat seed production and dry matter accumulation, suggesting that they are the least competitive with wild oat. Didon (2002) observed that barley cultivar Jessica, which had the earliest emergence, also had the fastest rate of stem extension, greatest number of leaves, tallest stature, and was consequently more competitive than cvs. Svani and Lina.

Growth habit and earliness of ground cover also varies considerably among cultivars. Dhaliwal and Froud-Williams (1993) found that barley with a prostrate growth habit reduced weed biomass more than erect cultivars due to early canopy establishment. Cultivars (cv. Parade and Slejpner) that were slow to establish ground cover were frequently less competitive than those with rapid ground cover. Similarly, winter wheat cultivars that achieved good early ground cover suppressed weed growth more than cultivars with less ground cover (Richards and Whytock, 1993).

Plant height is often correlated with improved competitive ability, especially in cereal crops (e.g. Challaiah et al., 1986; Baylan et al., 1991; Lemerle et al., 1996). Because of the vertical orientation of their leaves, more light reaches weeds growing beneath the canopy in cereals than in broad-leaved crops (Mohler, 2001a). Thus, height becomes an

important characteristic in determining varietal competitiveness. Numerous studies have documented the importance of plant height in varietal competitiveness. Barley cultivars that gave priority to height had a competitive advantage over those that allocated more resources to leaf growth (Didon, 2002). Challaiah (1986) noted that wheat height was better correlated with reductions in downy brome (*Bromus tectorum* L.) yield than was the number of tillers. Wheat cultivars that were taller and had denser canopies yielded more than shorter cultivars under weed competition (Lemerle et al., 1996). In addition, they found that 'old standard' cultivars suppressed weed growth more than current varieties, a claim commonly made based on the assumption that current varieties are dependent on chemical as opposed to cultural weed control. Taller Australian wheat varieties also were reported to have greater early vigor than short varieties (Richards, 1992). However, it is unlikely that breeders will select for taller varieties due to their inherently lower harvest index and greater susceptibility to lodging.

The most competitive cultivars frequently combine high yield with competitive ability. These cultivars are possible because several traits are combined and contribute to competitive ability. For example, high leaf area index or biomass, as well as height contribute to competitive ability in cereals (Baylan et al., 1991; Huel and Hucl, 1996). Challaiah et al. (1983) observed that several high yielding winter wheat cultivars also had high percentage light interception and low weed densities. Similarly, barley varieties of similar height were varied in percent light interception and thus, wild oat suppression (Lanning et al., 1997). In contrast, Bridges and Chandler (1988) observed no difference in the competitiveness of three cotton varieties of differing heights with *Sorghum halepense* (L.).

Numerous problems currently limit the potential to select for cultivars with improved competitive ability. The competitive ability of cultivars across experiments conducted at different locations or in different years often exhibits great variation (Lemerle et al., 1996; Ogg and Seefeldt, 1999). This problem likely arises as a result of the many characteristics interacting to determine competitive ability and makes screening a large amount of genotypes for competitive ability arduous. Furthermore, the only conclusive way to test for actual differences in competitive ability attributed to a single characteristic

is to compare near isogenic lines differing only in the trait of interest (Forcella, 1987). Nevertheless, cultivar screening trials could still be useful in identifying those genotypes better able to compete with weeds. In fact, some segregating populations that result from hybrids are grown in competition with weeds during selection, and thus the competitive abilities of genotypes can have a profound influence on the results of breeding programs (McBratney and Frey, 1993). However, current plant breeding programs are often directed towards improving grain yield and quality, and few programs are devoted to selecting for increased weed competition or competitive ability.

### **2.4.3 Seed size**

The ability of plants to compete and produce high yields may be profoundly affected by the size of the seed from which the plant was produced (Peterson et al., 1989; Geritz et al., 1999; Xue and Stougaard, 2002). Seed size affects numerous ecological processes including seed dispersal and establishment (Leishman et al., 2000), as well as plant attributes such as growth form (Maranon and Grubb, 1993), plant height (Leishman and Westoby, 1994), and leaf area (Peterson et al., 1989). The production of seeds varying in size results from physiological and ecological trade-offs. From an ecological perspective, the seed size/number trade-off (SSNT) theory proposes that seed size variation is the product of a trade-off in resource allocation for producing either few large seeds or many small seeds (Leishman, 2001). Seed size variation can also occur as a result of genetic differences, interplant competition for resources, or location of the seed on the inflorescence, which affects resource allocation to each seed (Wood et al., 1977). In many species, resource availability affects reproductive output via adjustments in allocation through the SSNT (Arntz et al., 2002). Currently, the SSNT model is the only explanation for the variety of seed sizes that exist within plant communities (Rees and Westoby, 1997). Selective pressures may favor the production of many small seeds for increased fitness (Leishman and Murray, 2001) or the production of few large seeds better able to establish and survive in heterogeneous environments (Westoby et al., 1992).



#### 2.4.3.1 Germination, emergence, and seedling vigor

Several studies have investigated the relationship between the germination and emergence of seeds varying in size with mixed results. Large pearl millet seed (*Pennisetum typhoides* L.) had 13% greater germination than small seed (Kawade et al., 1987), while small seeds of *Crepis tectorum* (L.) were more likely to resist germination when buried in soil than were large seeds (Andersson, 1996). The author suggested this may be due to larger *C. tectorum* seeds having a relatively thinner seed coat. In contrast, Martinková et al. (1999) noted no relationship between *Rumex obtusifolius* (L.) achene size and germination percentage. Likewise, Cideciyan and Malloch (1982) found no difference in total germination between large and small *Rumex crispus* and *R. obtusifolius* seed. Small seed of both species, however, had a faster germination rate than large seed, although small seed produced consistently smaller plants. Small wheat seed germinated faster than large seed at several temperature and osmotic potential combinations (Lafond and Baker, 1986a). Unfortunately, many of these studies were carried out under field conditions rather than in controlled environments, which introduces a large amount of variation.

Under most conditions, large seed appears to produce larger, more vigorous seedlings. Kaufmann and Guitard (1967) identified a positive relationship between seed size, seedling vigor, and plant yield in 2 barley cultivars. Likewise, Kaufmann and McFadden (1963) reported visible differences in seedling vigor and a significant yield advantage with the use of large compared to small seed within the same barley cultivar. Seedling vigor in wheat has also been positively related to seed size. However, much early seed size work must be interpreted with caution because the seed was sown either at equal number or weight per unit area (Wood et al., 1977). Taking this into consideration, Lafond and Baker (1986b) determined that seed size differences in wheat accounted for approximately 50% of the variation in seedling shoot dry weight. Although plants grown from small seed emerged faster, they produced less dry weight and were less vigorous than those grown from large seed. Bockus and Shroyer (1996) examined the influence of seed size on wheat seedling vigor and forage yield by seeding both by seed number and volume per unit area. Their results showed that when sown at the same number of seeds

per square meter, large wheat seed gave rise to 16-74% more plants per unit area than small seed. However, when sown by volume, small seed produced stands that were similar to or more dense than those from large seed. Ultimately, these differences in vigor between seed size classes are a product of initial embryo size (Lopez-Castañeda et al., 1996).

#### **2.4.3.2 Early season growth and development**

Increased seedling vigor from large seed also affects plant development factors including rate of leaf appearance, growth, and size of leaves. Rate of seedling growth and size of the first two leaves in barley were significantly greater when grown from large seed (Kaufmann and Guitard, 1967). Shoot and dry weights, total leaves, culms, tillers, and main stem leaf area were higher for winter wheat plants established from large seed compared to those from small seed (Peterson et al., 1989). Both Lafond and Baker (1986b) and Aiken and Springer (1995) concluded that plants established from large seed had faster growth rates after emergence in wheat and switchgrass (*Panicum virgatum* L.), respectively. This may be attributed to faster germination, early shoot growth, and early adventitious root growth in plants derived from large seed (Smart and Moser, 1999). This begs the question of whether greater root growth of plants from large seed will be more tolerant to stresses such as drought and salinity. Although the former has not been tested, wheat plants established from large seed were more tolerant to salinity and produced higher yields than plants established from small seeds (Grieve and Francois, 1992). Therefore, the benefits from planting large seed may be a cost-effective management tool for improving plant response to and productivity in environmentally stressed regions not generally conducive to vigorous plant growth.

#### **2.4.3.3 Yield and competitive ability**

The relationship between seed size and yield, like that of germination, also appears to be somewhat ambiguous. Yield components in wheat have been significantly correlated

with seed size (Austenson and Walton, 1970). Using multiple regression, the authors demonstrated that approximately 3 to 5% of the variation in total yield, grain yield, heads per plant and seed per plant could be explained by initial seed weight. Furthermore, the effect of seed size appeared to be similar among cultivars. Similarly, yield from large barley seed was 11% greater than from small seed (Demirlicakmak et al., 1963). Likewise, Kaufmann and McFadden (1960) noted that barley plots established from small seed yielded 20% less than those established from large seed. Alternatively, emergence, head number, and grain yield of soft red winter wheat cultivars in Illinois were not affected by seed size (Mian and Nafziger, 1992). In fact small seed yielded more than large seed in some years. Dhillon and Kler (1976) also noted that small-seeded soybean (*Glycine max* L. Merr.) yielded more compared with that of large seed. However, these discrepancies may be highly related to growing conditions, with large seed becoming more advantageous under less favorable conditions.

It is important to note that most of the previously mentioned studies were conducted under weed-free conditions. Several authors have documented that the relative effect of seed size seems to be enhanced when grown in competition with weeds. Xue and Stougaard (2002) found that spring wheat competitiveness with wild oat increased as seed size and seeding rate increased. Wild oat panicle numbers were reduced by 15%, while biomass and seed production of the weed were reduced by 25% with the use of large seed as compared to small seed. Wheat yields were improved 12 and 18% with the use of higher seeding rates and large seed, respectively, in the presence of wild oat competition (Stougaard and Xue, 2004). In *Desmodium paniculatum* (L.) D.C., a broad-leaved perennial herb, seedling growth from larger seed was greater than from smaller seed (Wulff, 1986). The author concluded that large seeds have an advantage over small, particularly when grown in competition with other species. Thus, it appears that both the competitive effect and competitive response of plants to competition can be improved with the use of large seed. Unfortunately, studies comparing seed size effects among genotypes in response to weed interference are lacking and therefore, recommendations must be limited. Nonetheless, seed size has become one of the prime considerations of both the seed industry and breeding programs.

### **3.0 Influence of wild oat relative time of emergence and density on oat – wild oat competition**

#### **3.1 Introduction**

Saskatchewan is currently the largest producer of oat in Canada (Statistics Canada, 2004) and one of the largest in the world (FAOSTAT, 2004). In 2003, Saskatchewan producers harvested an estimated 1,202,900 t of oat for grain on 668,020 ha of cropland (Saskatchewan Agriculture, Food, and Rural Revitalization, 2004). Since grain yield and quality determine a large portion of the value of an oat crop to producers, it is essential to maintain high standards of both. Nevertheless, oat production in western Canada continues to suffer from significant reductions in both yield and quality due to wild oat (*Avena fatua* L.) interference (Wildeman, 2004). The negative outcome of wild oat competition on crop yield and profitability is extensive, with annual losses in western Canada estimated at \$500 million (Manitoba Agriculture, 2001). In recent surveys, wild oat was found to persist on approximately 57%, 51%, and 46% of fields in Manitoba, Saskatchewan, and Alberta, respectively (Leeson et al., 2002a; Leeson et al., 2003; Leeson et al., 2002b). Although a troublesome weed in wheat (*Triticum aestivum* L.) (Carlson and Hill, 1985) and barley (*Hordeum vulgare* L.) (O'Donovan et al., 1985), wild oat is most problematic in oat. This is due to the genetic similarity between the two species, which precludes selective herbicide use to control wild oat.

Weed competition can affect crop quality, but studies investigating this relationship have produced ambiguous results. Competition between wheat (*Triticum aestivum* L.) and wild mustard (*Brassica kaber* (D.C.) L.C. Wheeler) for available nitrogen led to marked declines in wheat protein (Burrows and Olson, 1955). Similarly, in a survey of 60 farms in Manitoba, Friesen et al. (1960) noted that both wheat and barley protein concentration and grain yield were reduced under wild oat competition. Soybean test weight was reduced 2, 3, and 10% for each plant per meter of row increase in the

densities of sicklepod (*Senna obtusifolia* L.), redroot pigweed (*Amaranthus retroflexus* L.), and common cocklebur (*Xanthium strumarium* L.), respectively (Ellis et al., 1998). In contrast, 300 wild oat (*Avena sterilis* L.) plants m<sup>-2</sup> did not reduce barley (*Hordeum vulgare* L.) thousand kernel weight (Torner et al., 1991). In oat, increasing kochia (*Kochia scoparia* L.) density to 30 plants m<sup>-2</sup> did not affect test weight, kernel weight, groat percentage, groat ash, starch, or total  $\beta$ -glucan content (Manthey et al., 1996). Likewise, increasing wild oat density (180 plants m<sup>-2</sup>) did not affect groat or plump kernel percentages, fat, or protein concentrations among six western Canadian oat genotypes (Wildeman, 2004). Although wild oat competition did cause statistically significant increases in percentage thin kernels and corresponding decreases in thousand kernel and test weight, the differences were small and economically unimportant.

The potential reproductive output of wild oat is substantial, with up to 2000 seeds per plant produced in the absence of competition (Chancellor, 1976). However, estimates of wild oat seed production are highly sensitive to a number of factors including emergence time, plant density, crop competition, and environmental conditions. Although delays in wild oat emergence reduce its fecundity (Peters and Wilson, 1983), seed production from late emerging wild oat may still be a concern in oat. The inability to selectively remove wild oat from oat likely results in prolific wild oat seed production, causing large wild oat seedbank inputs that could eventually become problematic. However, no information exists regarding the influence of wild oat time of emergence and density on oat growth and yield, or the resulting wild oat reproductive output and contamination. This information would be valuable for the prediction of wild oat population dynamics and potential future infestations.

Despite the increase in oat acreage in recent years, relatively little research has been conducted towards improving the ability of oat to compete with wild oat. Current oat breeding programs are directed towards improving crop yield and quality characteristics, and little effort is devoted to selecting for increased competitive ability with wild oat. Planting more competitive oat cultivars could reduce the negative impact of wild oat on oat yield. A fundamental component in the development of more competitive oat cultivars may be time of emergence. Earlier emerging oat would likely be better able to

exploit resources initially, ultimately contributing to more competitive plants. However, no information is available regarding the effect of wild oat time of emergence and density on oat yield and quality. Moreover, to the best of my knowledge, no study has examined the relationship between weed density and time of emergence as affecting crop quality. Because much of the oat crop is sold for human consumption, its value and marketability are highly dependent on physical kernel quality. Therefore, the objectives of the present study were two-fold. The primary objective was to quantify the effect of wild oat density and relative time of emergence on oat yield loss, wild oat contamination, and wild oat seed production. The secondary objective was to elucidate the effects of relative time of emergence and density of wild oat on oat physical kernel quality, or more specifically, plump and thin kernel percentages, thousand kernel weight, and test weight.

## **3.2 Materials and Methods**

### **3.2.1 Experimental design and location**

Field experiments were conducted at the Agriculture Canada Research Station at Indian Head (lat 50°32', long 103°40'), SK, and at the Kernen Crop Research Farm (KCRF) near Saskatoon (lat 52°09', long 106°33'), SK, in 2002 and 2003. The site at Indian Head was located on an Indian Head heavy clay soil (Rego Black Chernozem; 10% sand, 27% silt, and 63% clay) in the Aspen Parkland ecoregion (Acton et al., 1998), while the Saskatoon site was located on a Sutherland series clay soil (Bradwell Dark-brown Chernozem; 26% sand, 34% silt, and 40% clay) in the Moist Mixed Grassland ecoregion (Acton et al., 1998). The 2002 Kernen site was lost to drought. The experiment was a 2 factor (wild oat density [4] x wild oat relative time of emergence [5]) randomized complete block design with four replicates resulting in 80, 2- by 8-m experimental units per location. Plots were established on wild oat-free areas of barley stubble at Indian Head in both years and on wheat stubble at KCRF in 2003. All sites received a preseeding glyphosate burn-down at 0.90 kg ai ha<sup>-1</sup> prior to or immediately following planting to control emerged weeds.

### 3.2.2 Experimental procedures

Wild oat seed was collected in the fall of 2001 as dockage from a local grain terminal, cleaned, and stored at ambient air temperature before planting. Wild oat was planted every 50 growing degree days (GDD) using a double-disc, minimum disturbance seeder at target densities of 0, 20, 80, and 320 plants m<sup>-2</sup>. GDD were calculated using the following equation:

$$GDD = \sum \left[ \left( \frac{T_{max} + T_{min}}{2} \right) - T_{base} \right] \quad [3.1]$$

where  $T_{max}$  is the daily maximum air temperature,  $T_{min}$  is the daily minimum temperature, and  $T_{base}$  is the assumed base temperature (0 C) for wild oat growth (Shirtliffe et al., 2000). Wild oat seeding rates were adjusted for germination test results and an assumed 10% seedling mortality. Wild oat planting occurred relative to the crop (seeded at the third wild oat planting, termed 0 GDD treatment), providing four emergence times: 50 and 100 GDD before crop emergence and 50 and 100 GDD following crop emergence. Planting on a GDD basis standardized planting dates by accounting for differences in biological activity based on air temperature.

At the third wild oat planting (0 GDD treatment) oat (cv. 'AC Assiniboia') was seeded perpendicular to the wild oat treatments at a target density of 250 plants m<sup>-2</sup>. This occurred over the front 6 m of the plot, providing a 2 m area at the back of the plot that allowed wild oat emergence to be monitored, circumventing having to differentiate between the two species. Oat was planted using a double-disc, minimum-disturbance plot seeder at KCRF and a no-till plot seeder with hoe openers at Indian Head. Although no oat was planted in the 2 m oat-free areas at the back of the plot, the seeder passed through the soil to simulate in-plot disturbance during planting. Fertilizer was side-banded on the entire experimental site at both locations at oat seeding based on soil test recommendations. Broadleaf weed control was achieved using a tank-mix of fluroxypyr at 0.14 kg ai ha<sup>-1</sup> and clopyralid at 0.67 kg ai ha<sup>-1</sup> at Indian Head in 2002, and clopyralid at 0.1 kg ai ha<sup>-1</sup> plus MCPA ester at 0.56 kg ai ha<sup>-1</sup> at both Indian Head in 2003 and

KCRF in 2003. Any weeds other than wild oat that survived herbicide treatment were manually removed.

Wild oat emergence was monitored daily on two individual 1 m rows per plot in the oat-free area, while oat emergence monitoring was also conducted daily on two individual 1 m rows in the plots that were free of wild oat (0 plants m<sup>-2</sup> treatment). The wild oat and oat actual densities were determined by counting plants in two 1 m rows, 3-4 weeks after crop emergence. Shoot biomass of both species, as well as wild oat reproductive output (expressed as seeds m<sup>-2</sup>) were measured at the oat soft dough stage (Zadoks 85) in two 50- by 50-cm quadrats at the front and back of each plot (Zadoks et al., 1974). Wild oat and oat were hand separated and panicle counts were performed on wild oat. Wild oat seed production was estimated on 10 panicles by counting the number of fertile spikelets and multiplying by two, as wild oat typically has 2-3 seeds per spikelet (Sharma and Vanden Born, 1978). Grain yield was determined for the entire 6 m plot on a clean weight basis after drying to a uniform moisture content. Grain yields were subsequently adjusted for the percentage of wild oat in the harvested oat grain sample.

Each harvested oat grain sample was cleaned using a dockage tester and with subsequent manual removal of all wild oat. Sound oat grain was stored in paper bags at room temperature (22°C). The percentage of wild oat in the harvested oat grain sample was determined by hand-removing all wild oat seed from a 300 g sample from each plot. Kernel weight, as expressed by thousand kernel weight (TKW), was calculated by determining the weight of 500 kernels and multiplying by two. Test weight was measured as specified by the Canadian Grain Commission's Official Grain Grading Guide (2004). The percentage of thin kernels in each grain sample was recorded from a 300 g sample as the portion of the grain sample mass passing through a 1.95 mm x 8.33 mm (5/64" x 3/4") slotted sieve after shaking for 90 s, and the percentage plump kernels as the portion of the grain sample mass retained on a 2.15 mm x 8.33 mm (5.5/64" x 3/4") slotted sieve after shaking for 90 s. These four parameters, as well as groat percentage, weight, and composition, are most frequently used to describe oat quality (Doehlert et al., 2001). Groat percentage was not determined in this study as groat percentages among



western Canadian oat genotypes have been shown to be unaffected by wild oat competition (Wildeman, 2004).

### **3.2.3 Statistical analysis**

#### *Yield Loss calculations*

Percentage oat yield loss was calculated by subtracting the oat yield in each experimental unit from the maximum observed yield within each wild oat seeding date treatment in each block, dividing by the maximum observed yield, and multiplying by 100. This resulted in yield losses in some experimental units that did not contain wild oat only because the maximum yield for that particular seeding date treatment in the block occurred in a plot with wild oat. By using maximum yield to calculate yield loss, one tends to bias yield loss figures upward. However, when the average yield of all weed-free plots are used to calculate yield loss, percentage yield loss can take on illogical negative values, e.g., Dieleman et al. (1995), Lindquist et al. (1996), or Bosnic and Swanton (1997). Often the objective of fitting yield loss functions is for incorporation into bioeconomic models to be used by growers and agronomists. Negative values become problematic in these situations because it is better to make cautious management decisions based on upwardly biased yield loss figures than careless decisions based on negative yield losses that tend to bias values downward (Jasieniuk et al., 1999).

#### *Regression Analysis*

Analysis of variance using SAS general linear model procedures (SAS Institute Inc., 1996) was initially performed to test the significance of wild oat density, relative time of emergence, and interactions between emergence time and density on all measured variables. Due to significant year and location effects as well as unique wild oat densities in each experimental unit, data were analyzed within site-years. Means were separated using Fisher's protected least significant difference with treatment effects declared significant at  $P < 0.05$ . Variables that were significantly affected by target wild oat densities and relative time of emergence were then analyzed further using nonlinear regression analysis. Cousens (1988, 1991) suggested the use of nonlinear regression as

both a more appropriate and useful means of yield and yield component analysis compared to multiple ranges tests. Because the objective is to determine the response of crop and weed yield and yield components to wild oat time of emergence and density, it is more informative to describe the response surface of this relationship rather than test whether yield loss differed among wild oat treatments (which in some cases may require a 10 to 15% yield difference before multiple range tests could separate treatment differences).

Median emergence time (time to 50% emergence) of each wild oat emergence time treatment relative to the crop (in GDD) was determined for use in the time of emergence equation fitting process that follows this section. Median emergence time was described by the fitting the following logistic function to each experimental unit:

$$P_t = 1/[1 + e^{a(-t+b)}] \quad [3.2]$$

where  $P_t$  is the proportion of seeds emerged at time  $t$ ,  $t$  is thermal time in GDD accumulated since the initiation of each wild oat emergence date treatment,  $a$  is the estimated rate of emergence (number of emerged seeds GDD<sup>-1</sup>), and  $b$  is the estimated median emergence time (GDD) for each species in each experimental unit. Final emergence percentage (collected from field data) and median emergence time ( $b$  parameter in equation above) were then subjected to analysis of variance using PROC GLM (SAS Institute Inc., 1996).

Oat yield loss was analyzed by fitting yield loss data to the following hyperbolic equation (Cousens et al., 1987):

$$Y_L = \frac{ID}{e^{CT} + ID/A} \quad [3.3]$$

where  $Y_L$  is percent yield loss,  $D$  is wild oat density (plants m<sup>-2</sup>),  $T$  is the observed median time of emergence of the weed relative to the crop in GDD calculated with Equation 2, and  $I$ ,  $A$ , and  $C$  are fitted model parameters. Parameter  $I$  is the percent yield loss per unit weed as  $D \rightarrow 0$  at  $T = 0$ ,  $A$  is the estimated maximum yield loss as  $D \rightarrow \infty$ , and  $C$  is the rate at which  $I$  declines exponentially as  $T$  becomes larger, essentially modifying the effect of  $I$  based on the relative emergence time of wild oat.

The relationship of wild oat biomass to varying wild oat densities and relative time of emergence was analyzed by fitting the data to the following asymptotic function modified from that proposed by Watkinson (1980) to included the exponential effect of increasing emergence time:

$$Y_w = \frac{W_m D}{e^{CT} + aD} \quad [3.4]$$

where  $Y_w$  is wild oat biomass ( $\text{g m}^{-2}$ ),  $W_m$  is the maximum potential biomass per wild oat plant,  $a$  is the area needed to achieve  $W_m$ ,  $D$  is wild oat density ( $\text{plants m}^{-2}$ ),  $T$  is the observed median time of emergence of the weed relative to the crop in growing degree days (GDD) (base temperature =  $0^\circ\text{C}$ ), and  $C$  is the rate at which  $W_m$  declines exponentially as  $T$  becomes larger.

The relationship between wild oat seed production and wild oat density and relative time of emergence was described with the following equation (Bosnic and Swanton, 1997):

$$S_d = \frac{aD}{e^{CT} + aD / B} \quad [3.5]$$

where  $S_d$  is wild oat seed production (number of seeds  $\text{m}^{-2}$ ),  $D$  and  $T$  are as described above, and  $a$ ,  $B$ , and  $C$  are fitted model parameters. Parameter  $a$  is the number of wild oat seeds produced per wild oat plant as  $D \rightarrow 0$  at  $T = 0$ ,  $B$  is the maximum wild oat seed production  $\text{m}^{-2}$  as  $D \rightarrow \infty$ , and  $C$  is the rate at which  $a$  declines exponentially as  $T$  becomes larger, essentially modifying the effect of  $a$  based on the relative emergence time of wild oat.

The relationship of percent wild oat contamination to wild oat density and relative time of emergence was described with a similar equation:

$$P_{wo} = \frac{pD}{e^{CT} + pD / B} \quad [3.6]$$

where  $P_{wo}$  is wild oat contamination or the percentage of wild oat in the harvested oat grain sample as a function of wild oat density ( $D$ ) and time of emergence relative to the crop ( $T$ ),  $p$  is the percentage wild oat contamination per wild oat plant as  $D \rightarrow 0$  at  $T = 0$ ,  $B$  is the maximum percentage wild oat contamination as  $D \rightarrow \infty$ , and  $C$  is the rate at

which  $p$  declines exponentially as  $T$  becomes larger, essentially modifying the effect of  $p$  based on the relative emergence time of wild oat.

All functions were fit to the data separately for each location and year. Regressions were performed on all data using a nonlinear least-squares regression procedure (PROC NLIN; SAS Institute Inc., 1996). All regressions except yield loss were weighted by  $1/\sqrt{\text{wild oat density}}$  to account for heterogeneity of error variances (Schabenberger and Pierce, 2002). The Marquardt iterative procedure was used to find the values of the model parameters that minimized the sums of the squared deviations between observed and fitted values. It has been previously suggested that a test for model lack of fit be conducted involving the partitioning of the residual sum of squares (RSS) into lack of fit error and pure experimental error (Draper and Smith, 1981). However, this could not be conducted because wild oat densities were unique for each plot and therefore no replication was evident to provide for an estimation of pure error. Consequently, an approximate  $F$  statistic and the coefficient of determination  $R^2$  were used to evaluate the goodness of fit of each regression model to each individual data set. The approximate  $F$  statistic was calculated by (using SAS's Nonlinear Summary Statistics output):

$$F = \frac{\text{Regression Mean Square Error}}{\text{Residual Mean Square Error}} \quad [3.7]$$

Where:

$$MSE = \frac{\text{Corrected Total Sum of Squares} - \text{Residual Sum of Squares}}{\text{Regression Degrees of Freedom}} \quad [3.8]$$

$R^2$ , or the proportion of the total variance in each independent variable explained by each model, is termed a *Pseudo  $R^2$* , and was calculated by (Schabenberger and Pierce, 2002):

$$R^2 = 1 - \left[ \frac{\text{Residual Sum of Squares}}{\text{Corrected Total Sum of Squares}} \right] \quad [3.9]$$

Data sets for all regressed variables were compared for differences in parameter estimates using the extra sum of squares principle for nonlinear regression. The intricacies of this procedure will not be discussed here but for a thorough description see either Lindquist et al. (1996) or Ratkowsky (1983). In short, the procedure is a step-wise process that tests whether the model parameters vary significantly among site-years. If model parameters

did not vary among site-years, data from all site-years can be pooled into a combined model. Alternatively, if model parameters did vary significantly among site-years, 95% confidence intervals (C.I.s) around the parameter estimates are used to determine which data sets differed in their values of each model parameter.

#### *Oat Quality Analysis*

Thousand kernel weight, test weight, and the percentage of plump and thin kernels data were subjected to a two-way analysis of variance (wild oat density x time of emergence) using the general linear model procedure of SAS (SAS Institute Inc., 1996). The responses of oat TKW, test weight, and percent plump and thin kernels to wild oat relative time of emergence and density were tested for linearity with orthogonal contrasts. The regression coefficients for the quadratic terms were not significant in all cases and are therefore not presented. Due to significant year and location effects, all data were analyzed within site-years. Data were also analyzed within time of emergence and density treatment combinations when significant interactions existed. Means were separated using Fisher's protected least significant difference with treatment effects declared significant at  $P < 0.05$ . Regression analysis was not performed because wild oat densities were unique for each experimental unit and therefore no estimation of pure error could be provided for regressions.

### **3.3 Results and Discussion**

Wild oat median emergence times varied considerably among site-years (Table 3.1). Although median emergence times at Indian Head in both years were generally 50 GDD apart as targeted, dry soil conditions in early May followed by frequent showers (Table 3.2) led to variable median emergence times at Kernen in 2003. Wild oat median emergence time was generally greater in those treatments that emerged before the crop than in those that emerged subsequent (Table 3.1). Likewise, final emergence also varied significantly between years and seeding dates (Table 3.1). At KCRF 2003 and Indian Head 2002, wild oat that emerged after oat had higher emergence than those that emerged before. Final wild oat emergence in these 2 years ranged from 47 to 107%.

**TABLE 3.1** Seeding date, accumulated thermal time, observed emergence, median emergence time, and final emergence percentage for wild oat emergence treatments as well as oat at Indian Head (2002, 2003) and Kernen (2003). Median emergence times, or the time to 50% emergence, were estimated by fitting wild oat emergence data to Equation 2.

Site-year	Target Emergence	Seeding Date	ATT†	Observed Emergence‡	MET§¶	Final Emergence¶
	GDD#		GDD	GDD	GDD	%
Indian Head 2002	-100	May 10	0	-92	256a	57.0b
	-50	May 17	57	-56	235b	55.2b
	0	May 27	135	5	218c	65.2b
	50	May 29	189	35	193d	88.5a
	100	May 31	224	57	182d	107.7a
	TO††	May 27	135	0	214c	88.2a
Indian Head 2003	-100	May 5	0	-110	192ab	25.7b
	-50	May 12	50	-61	192ab	20.8c
	0	May 20	126	-14	163c	24.1c
	50	May 23	176	57	184abc	28.2bc
	100	May 26	224	122	201a	21.5c
	TO	May 20	126	0	175bc	89.9a
Kernen 2003	-100	May 6	0	-30	165b	46.7c
	-50	May 12	47	-32	161b	70.5ab
	0	May 17	123	40	196a	56.6bc
	50	May 21	149	101	214a	74.3ab
	100	May 25	190	112	166b	86.8a
	TO	May 17	119	0	121c	88.5a

† ATT, Accumulated Thermal Time at each wild oat planting date calculated from the first wild oat planting date.

‡ Observed emergence calculated relative to the crop.

§ MET, Median Emergence Time.

¶ Means within the same column and site-year followed by the same lowercase letter are not significantly different ( $P < 0.05$ ) by LSD.

# GDD, accumulated growing degree days between target planting dates.

†† TO, Oat.

**TABLE 3.2** Monthly rainfall (mm) and the mean daily temperature (C) for Indian Head and Kernen from May until September in 2002 and 2003 and the long-term (30-yr) average.

Location	Month	Rainfall			Temperature		
		2002	2003	30-yr average†	2002	2003	30-yr average†
		mm			°C		
Indian Head	April	11	54	17	-0.6	4.3	4.0
	May	18	24	53	7.1	11.4	11.4
	June	115	18	79	15.8	15.5	16.1
	July	49	23	67	18.6	18.6	18.4
	August	98	11	53	15.7	19.5	17.5
	September	22	18	40	12.1	10.6	11.4
	Total	313	148	309	—	—	—
Kernen	April	11	35	14	-0.5	5.3	4.4
	May	T††	14	47	8.9	12.1	11.5
	June	73	31	61	17.3	16.0	16.0
	July	0	64	60	20.1	18.9	18.2
	August	86	31	39	16.6	20.9	17.3
	September	59	39	29	11.4	11.5	11.2
	Total	229	214	250	—	—	—

† 30-year averages obtained from Environment Canada (2004).

†† T, Trace.

Emergence at Indian Head in 2003 was exceptionally low (20-28%) and relatively variable. This may be due to minimal precipitation throughout the wild oat emergence period (Table 3.2). Soil moisture contents between 50 – 70% field capacity are known to be most conducive to wild oat germination (Sharma et al., 1976).

Wild oat seed production and contamination, as well as oat yield loss were not consistent among site-years, but were significantly affected by wild oat density and time of seedling emergence (Tables 3.3 and 3.4). Moreover, observed wild oat densities and times of seedling emergence were different than those targeted (Table 3.1) and varied considerably among experimental units. Consequently, nonlinear regression was performed on these variables and not surprisingly, extra sum of squares  $F$  tests indicated that a combined model among site-years could not be fit to any of the data (data not shown).

### **3.3.1 Effects of wild oat density and time of seedling emergence on oat yield loss**

The hyperbolic regression model, Equation 3, provided satisfactory fits for all oat yield loss data sets as indicated by the significance of approximate  $F$  tests, as well as  $R^2$  values ranging from 0.80 to 0.83 (Figure 3.1). Model parameter values were well estimated as indicated by the relatively small standard errors associated with parameter values (Table 3.5). Standard errors less than half of the numerical value of the estimate are considered to indicate good estimation (Koutsoyiannis, 1973). Oat grain yield and yield loss varied with site-year, time of wild oat seedling emergence, and wild oat density. Observed wild oat-free yields varied considerably among site-years, ranging from 2,910 to 3,780 kg ha<sup>-1</sup>. Differences in oat yields were likely due to the large variability in growing conditions among site-years (Table 3.2). Several authors have noted the importance of environmental conditions, soil type, and level of soil nutrients in causing discrepancies among crop yield and yield loss (O'Donovan et al., 1985; Dieleman et al., 1995; Knezevic et al., 1995).

Time of wild oat emergence had a large effect on oat yield loss. Oat yield loss from wild oat that emerged 92 GDD before the crop ranged from 0 to 71%, while losses when



**TABLE 3.3** Analysis of variance for tame oat height, biomass, panicles, grain yield, percentage plump and thin kernels, test weight, and thousand kernel weight as affected by wild oat density (WD) and wild oat emergence time (ET).

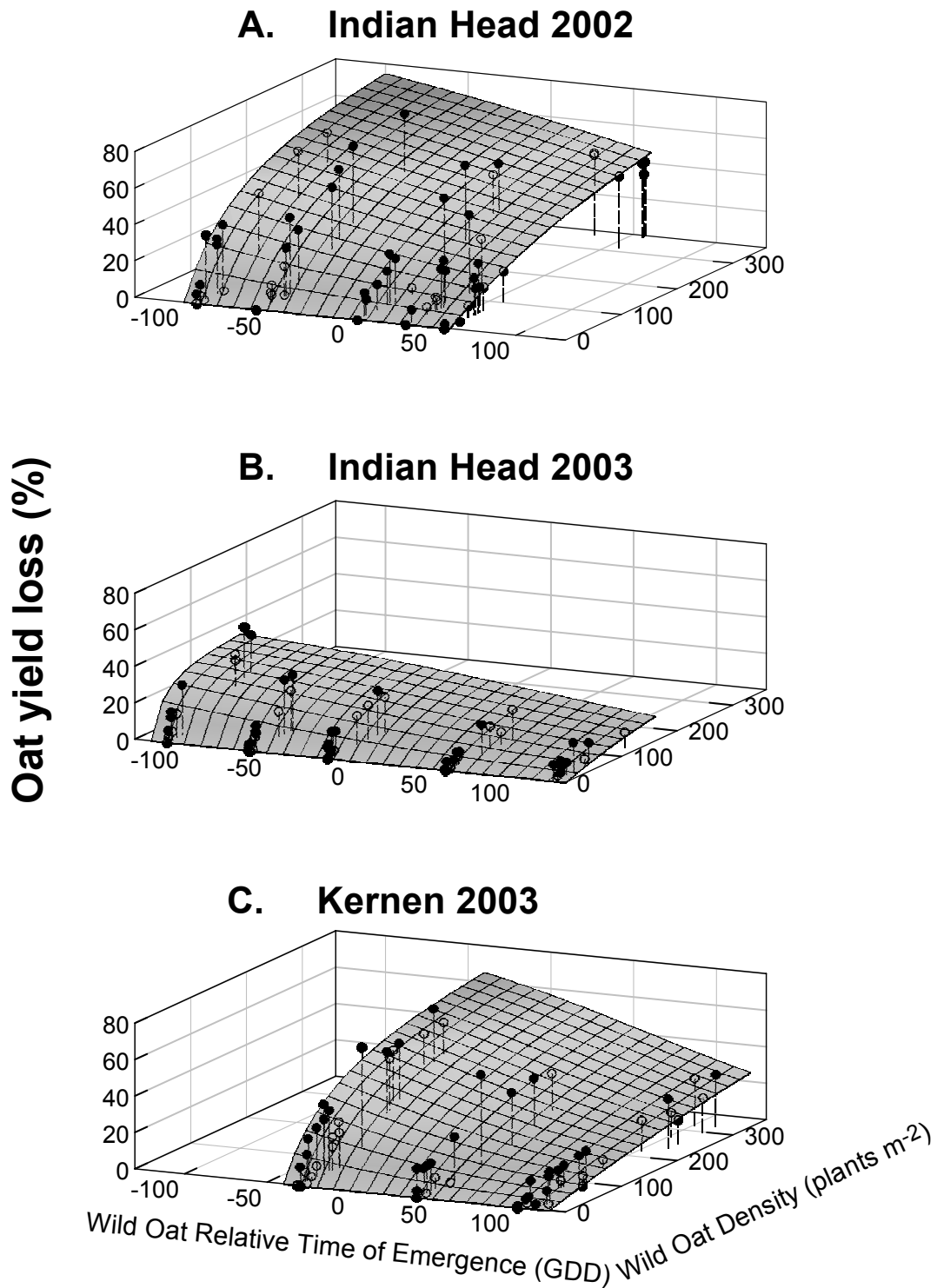
Source	df	Height	Biomass	Panicles	Yield	Plump Kernels	Thin Kernels	Test Weight	Thousand Kernel Weight
		cm	g m <sup>-2</sup>	no. m <sup>-2</sup>	kg ha <sup>-1</sup>	%	%	kg hl <sup>-1</sup>	g
Site-year (SY)	2	***	***	***	***	***	***	***	***
Wild oat Density (WD)	3	***	***	***	***	***	***	***	***
Emergence Time (ET)	4	*	***	***	***	*	***	NS	*
SY X WD	6	NS	***	**	***	NS	*	NS	**
SY X ET	8	**	NS	*	**	NS	NS	NS	NS
WD X ET	12	NS	**	***	***	NS	**	NS	NS
SY X WD X ET	16	NS	NS	**	NS	**	NS	NS	NS

\*, \*\*, \*\*\*, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

**TABLE 3.4** Analysis of variance for wild oat height, biomass, panicles, seed production, and wild oat contamination (percentage wild oat in the harvested oat grain sample) as affected by wild oat density (WD) and wild oat emergence time (ET).

Source	df	Height	Biomass	Panicles	Seed	Wild Oat
		cm	g m <sup>-2</sup>	no. m <sup>-2</sup>	Production	Contamination
Site-year (SY)	2	NS	***	***	***	***
Wild oat Density (WD)	3	***	***	***	***	***
Emergence Time (ET)	4	NS	***	***	***	***
SY X WD	6	***	***	***	***	***
SY X ET	8	NS	***	**	**	***
WD X ET	12	NS	***	***	***	***
SY X WD X ET	16	NS	*	NS	NS	***

\*, \*\*, \*\*\*, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.



**FIGURE 3.1** Percent oat yield loss predicted as a function of wild oat density and relative time of emergence at (A) Indian Head 2002, (B) Indian Head 2003, (C) Kernen 2003. Predicted values are represented by lines on the response surface and are the result of fitting the data to Equation 3.3:  $Y_L = ID / [(e^{CT}) + ID/A]$ . Parameter estimates are shown in Table 3.5. Points (●) represent observed values with open points (○) indicating observed values below the transparent response surface.

**TABLE 3.5** Observed mean weed-free oat grain yields and parameter estimates ( $\pm$  S.E.) for the crop yield model based on Equation 3.3 using growing degree days.

Location	Year	Observed mean weed-free yield‡§  kg ha <sup>-1</sup>	Parameter Estimates†			R <sup>2</sup>
			A‡	I	C‡	
			%	%		
Indian Head	2002	3780 (62)a	95.9 (12.7)a	0.400 (0.046)	0.008 (0.0011)b	0.83
Indian Head	2003	2912 (60)b	41.3 (3.5)b	0.494 (0.058)	0.011 (0.0013)a	0.82
Kernen	2003	2942 (99)b	83.3 (12.1)a	0.487 (0.070)	0.013 (0.0015)a	0.80
Pooled Model¶	—	—	81.4 (6.9)	0.414 (0.032)	0.009 (0.00074)	0.80

<sup>†</sup> $A$  is the asymptotic yield loss at high wild oat densities,  $I$  is the yield loss per unit wild oat as wild oat density approaches 0, and  $C$  is the rate at which  $I$  declines exponentially as relative time of wild oat emergence increases.  
<sup>‡</sup>Means within the same column followed by the same lowercase letter are not significantly different ( $P < 0.05$ ).  
<sup>§</sup>Observed mean weed-free yield was calculated as the yield of wild oat-free plots within each site-year averaged among all treatments.

<sup>¶</sup>Data combined using percent yield loss.

wild oat emerged 56 GDD after the crop only ranged from 0 to 46% at Indian Head in 2002 (Figure 3.1A). Wild oat seedlings that emerged before the crop caused greater yield loss than those that emerged after (Figure 3.1). For example, at Indian Head in 2002, a wild oat density of 100 plants  $\text{m}^{-2}$  emerging 92 GDD before the crop resulted in 45% yield loss compared to 20% for the same density of wild oat emerging 56 GDD after the crop (Figure 3.1A). Time of weed emergence relative to the crop has been reported to be more important than weed density when describing the relationship between barnyardgrass (*Echinochloa crus-galli* L.) and corn (*Zea mays* L.) yield (Bosnic and Swanton, 1997), and redroot pigweed (*Amaranthus retroflexus* L.) and soybean (*Glycine max* L. Merr) yield (Dieleman et al., 1995).

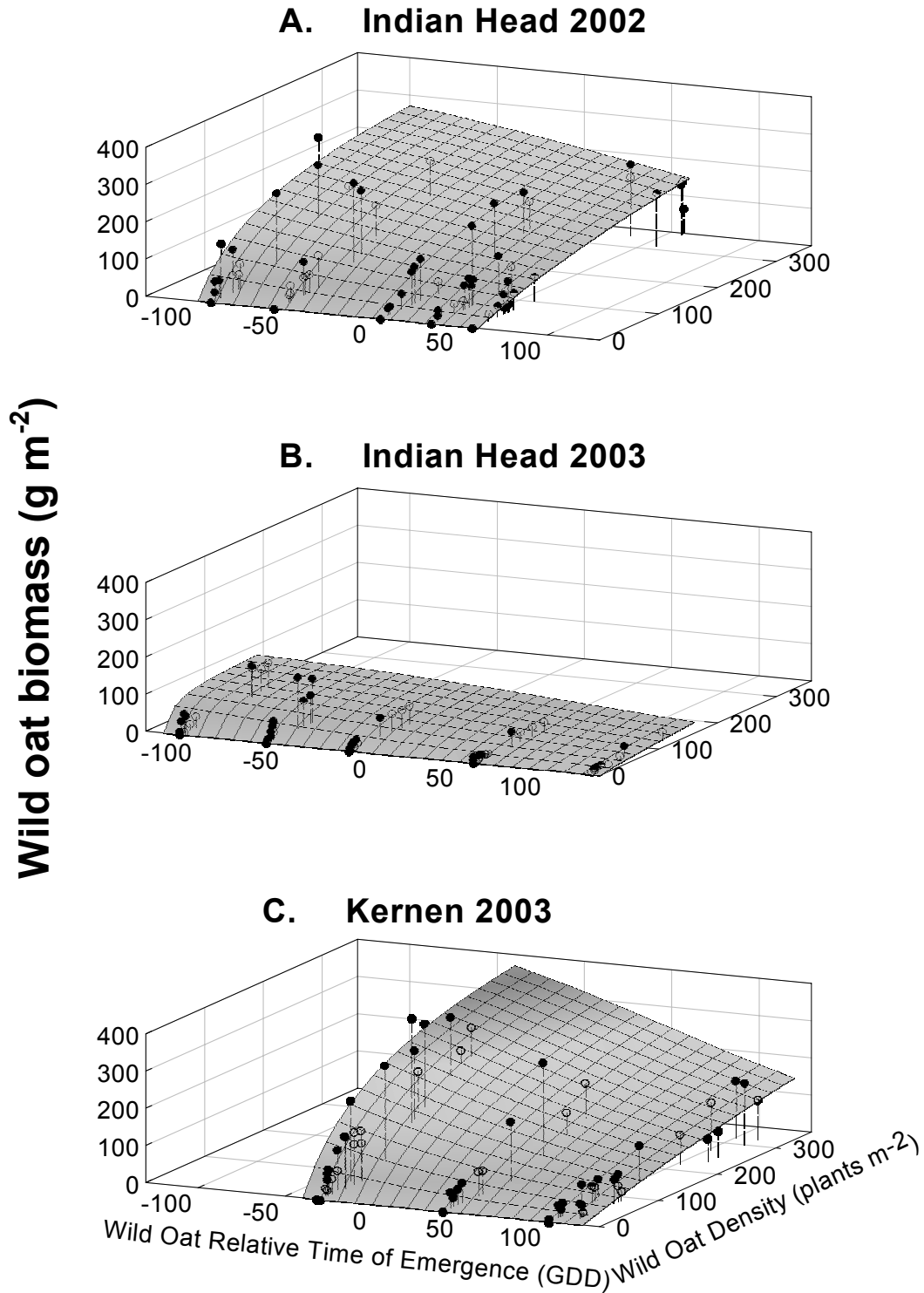
Maximum estimated yield loss ( $A$  parameter) differed among site-years ( $P < 0.05$ ) and was highest at Indian Head in 2002 (96%) and lowest at Indian Head in 2003 (41%) (Table 3.5). Large variability in these estimates may have been due to reduced wild oat populations, particularly at Indian Head in 2003, where the low wild oat densities observed were likely not high enough to properly fit parameter  $A$ . Obtaining appropriate asymptote estimates whereby yield loss values become asymptotic requires a great range of densities, often including unrealistically high plant populations. This illustrates one of the problems associated with the use of a rectangular hyperbolic function to describe yield loss data proposed by Cousens et al. (1987).

By contrast, estimates of  $I$  did not vary significantly ( $P < 0.05$ ) among site-years, indicating that percent yield loss caused per wild oat plant remained constant among site-years (Table 3.5). Although statistical tests indicated that  $C$  varied significantly ( $P < 0.05$ ) among site-years, the differences were small (Table 3.5). Nonetheless, higher values of  $C$  at Indian Head and KCRF in 2003 indicate that wild oat relative time of emergence had a greater effect on oat yield at these sites. Estimates of  $I$  and  $C$  also did not vary among years and locations in soybean (Dieleman et al., 1995) and corn (Bosnic and Swanton, 1997), suggesting that the influence of weed seedling emergence time on crop yield loss is reasonably consistent among crops, years, and locations.

Averaged over six site-years, Cousens et al. (1987) obtained estimated values of 1.00 and 0.59 for  $I$  in spring wheat and barley competing with wild oat in western Canada. These values are higher than those obtained here (0.446), suggesting that oat may be similar to or more competitive with wild oat than wheat and barley at low weed densities (Table 3.5). Likewise, the average estimated values for  $C$  were substantially lower for oat (0.012) compared to wheat (0.148) and barley (0.153) (averaged among six site-years) in western Canada (Cousens et al., 1987). This may indicate that yield loss in wheat and barley decreases faster than in oat when wild oat emergence is delayed. Therefore, late emerging wild oat seedlings may be more important in influencing yield loss in oat than in barley and wheat. It is important to note, however, that these are only generalizations and direct comparisons between the two studies cannot be made. Crop density in O'Donovan et al.'s (1985) study ranged from 151 to 202 plants  $\text{m}^{-2}$  compared to an average of 220 plants  $\text{m}^{-2}$  in the present study. Furthermore, they planted wild oat based on Julian date whereas the present study was planted on a GDD basis. Although a target wild oat emergence time of 8 days before or after the crop in O'Donovan et al.'s (1985) study corresponded to approximately 72 GDD in this study, no definite conclusions can be drawn from comparisons. However, had O'Donovan et al. (1985) planted and analyzed on a thermal time basis, values in the current study would have been more easily compared to Cousens et al. (1987) and inferences could have been drawn with more confidence. This demonstrates one advantage of conducting time of emergence studies based on thermal time.

### **3.3.2 Dependence of wild oat biomass on varying wild oat time of emergence and density**

Estimated wild oat biomass production varied with time of wild oat seedling emergence relative to oat, wild oat density, and site-year. Significance of approximate  $F$  tests and  $R^2$  values ranging from 0.68 to 0.82 indicated that Equation 4 provided a satisfactory fit for all wild oat biomass data sets (Figure 3.2). Moreover, the relatively small standard errors associated with all parameter estimates indicated that the model used provided good estimates of the data (Table 3.6).



**FIGURE 3.2** Wild oat biomass predicted as a function of wild oat density and relative time of emergence at (A) Indian Head 2002, (B) Indian Head 2003, (C) Kernen 2003. Predicted values are represented by lines on the response surface and are the result of fitting the data to Equation 3.4:  $Y_w = W_m D / [(e^{CT}) + aD]$ . Parameter estimates are shown in Table 3.6. Points (●) represent observed values with open points (○) indicating observed values below the transparent response surface.

**TABLE 3.6** Parameter estimates ( $\pm$  S.E.) for the wild oat biomass model based on Equation 3.4 using growing degree days.

Location	Year	Parameter Estimates†			$R^2$
		$a_{\ddagger}^{\dagger}$	$W_{m,\ddagger}^{\dagger}$	$C$	
		m <sup>-2</sup>	g plant <sup>-1</sup>		
Indian Head	2002	0.00373 (0.0012)b	1.29 (0.18)a	0.00963 (0.0016)	0.68
Indian Head	2003	0.0137 (0.0037)a	1.44 (0.26)ab	0.0129 (0.0021)	0.68
Kernen	2003	0.00495 (0.0013)b	2.44 (0.27)b	0.0125 (0.0014)	0.82
Pooled Model§	—	0.00545 (0.0011)	1.71 (0.18)	0.00759 (0.0011)	0.66

†  $a$  represents the area necessary to achieve  $W_m$ ,  $W_m$  is the maximum potential biomass produced per plant, and  $C$  is the rate at which  $W_m$  declines exponentially as relative time of wild oat emergence increases.

‡ Means within the same column followed by the same lowercase letter are not significantly different ( $P < 0.05$ ).

§ Data combined using wild oat biomass.



In all site-years, wild oat biomass was significantly ( $P < 0.05$ ) higher when emergence occurred prior to oat emergence as compared to when emergence followed oat (Figure 3.2). Averaged among all site-years, 100 wild oat plants  $\text{m}^{-2}$  emerging 40 GDD before the crop produced 49% more biomass than the same density emerging 50 GDD after the crop. The effects of time of wild oat seedling emergence on wild oat biomass production became less pronounced with increasing density. For example, 320 wild oat plants  $\text{m}^{-2}$  emerging 40 GDD before the crop only produced 35% more biomass than the same density emerging 50 GDD after the crop. Nonetheless, wild oat biomass production increased with increasing wild oat density in all site-years and time of emergence treatments. These results are consistent with previous studies that indicate higher wild oat biomass production in wild oat plants that emerge earlier than the crop compared to that when wild oat emergence follows crop emergence (Thurston, 1962; McBeath et al., 1970; Peters and Wilson, 1983). Likewise, redroot pigweed (*Amaranthus retroflexus* L.) produced more biomass per plant when emergence occurred at or before the 3-leaf stage of sorghum than at or after the 5.5-leaf stage (Knezevic and Horak, 1998). In that study, very little weed biomass was produced when weed emergence occurred after the 5.5-leaf stage of sorghum. Similar inferences can be drawn from the current study when wild oat emerged 50 GDD or more after the oat crop. Wild oat is most vulnerable to competition for soil resources during early growth stages (O'Donovan et al., 1985). Wild oat emerging before the crop was better able to exploit resources initially, contributing to highly competitive seedlings better able to compete for light, ultimately producing higher weed biomass and reduced crop biomass (data not shown) due to shading. Reduced light penetration and crop growth was also observed when wild oat was grown in mixtures with wheat (Cudney et al., 1991). Ensuring that wild oat emerges after the crop is essential given the highly positive correlation between biomass and seed production (Cousens and Mortimer, 1995).

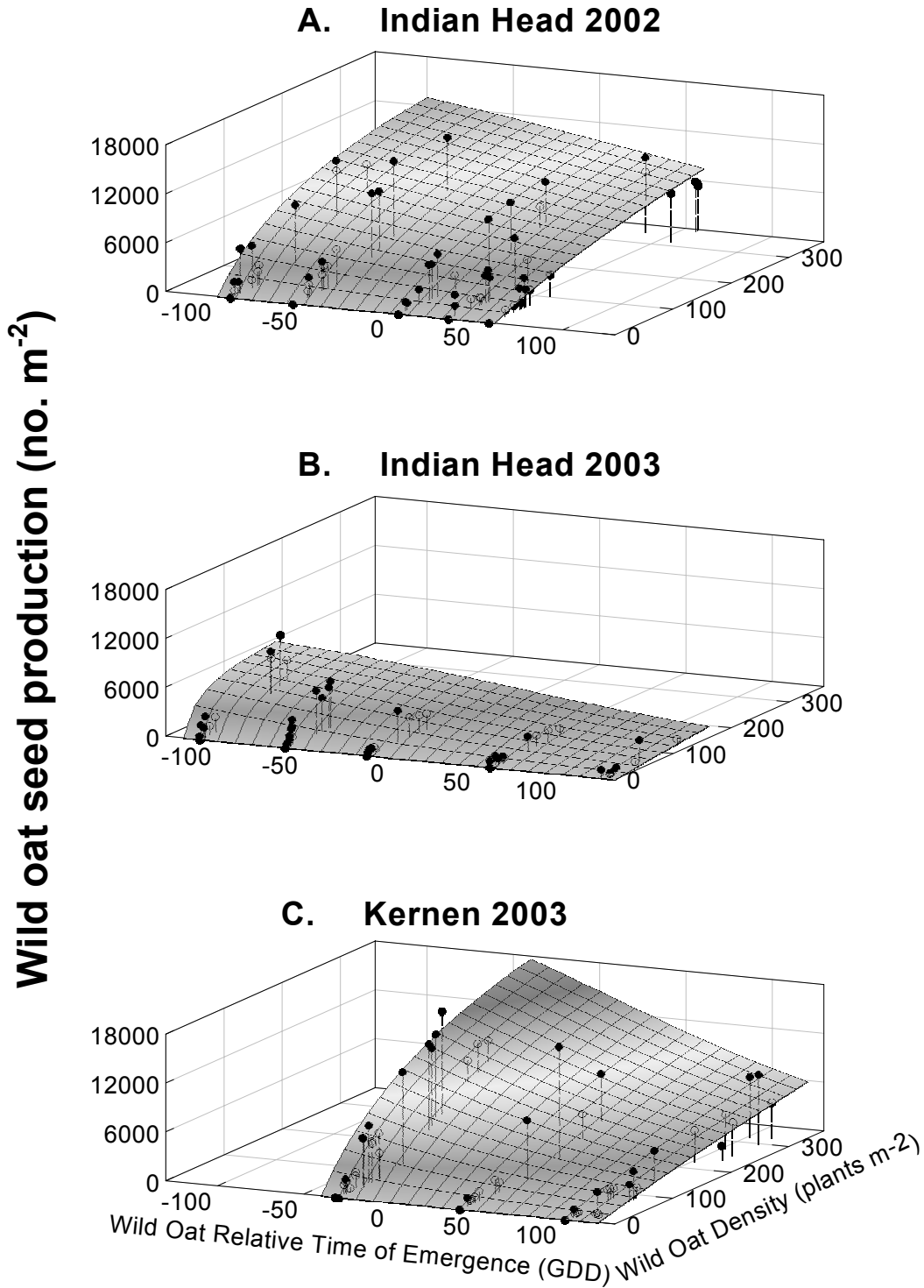
Maximum estimated biomass per wild oat plant ( $W_m$ ) was highest ( $2.44 \text{ g m}^{-2}$ ) at KCRF in 2003 and lowest ( $1.29 \text{ g m}^{-2}$ ) at Indian Head in 2002 (Table 3.6). Extra sum of squares tests indicated that  $W_m$  varied significantly among site-years, suggesting that maximum wild oat biomass production was variable among site-years. Likewise,  $C$  also

varied significantly among site-years, indicating that time of wild oat seedling emergence relative to the crop exhibits an inconsistent effect on wild oat biomass production. Coefficient instability may be due to a number of factors, including differences in environmental conditions (Table 3.2) and variability in the competitive ability of the crop among site-years. The area needed to achieve maximum biomass ( $W_m$ ),  $a$ , was highest at Indian Head in 2003 and was not variable among site-years. This value was likely highest at Indian Head in 2003 due to low growing season precipitation, resulting in an increase in the area of resources required to attain  $W_m$ . Nonetheless, coefficient stability, despite extreme environmental differences, implies that resource levels were similar among site-years. Parameter  $a$  values have been shown to increase with increasing time of emergence in soybean (*Glycine max* L. Merr.) monocultures (Watkinson, 1984). Although not examined directly in this study, values of parameter  $a$  would be expected to increase with increasing wild oat time of emergence due to the intensifying competition with oat at later emergence dates.

### **3.3.3 Reliance of wild oat seed production and contamination on density and time of seedling emergence**

Estimated wild oat seed production varied with time of seedling emergence relative to oat, wild oat density, and site-year (Figure 3.3). Fitting the data to Equation 5 provided a satisfactory fit for all wild oat seed production data sets as indicated by the significance of approximate  $F$  tests, as well as  $R^2$  values ranging from 0.72 to 0.82 (Figure 3.3). In all site-years, wild oat that emerged before oat produced higher amounts of seed than wild oat that emerged after the crop. For example, 100 wild oat plants  $m^{-2}$  emerging 30 GDD before the crop produced an estimated 8,200 seeds  $m^{-2}$  compared to only 2,100 seeds  $m^{-2}$  for wild oat emerging 112 GDD after the crop at KCRF in 2003 (Figure 3.3C).

Maximum estimated seed production  $m^{-2}$  ( $B$ ) was highest (28,000 seeds  $m^{-2}$ ) at KCRF in 2003 and lowest (7,800 seeds  $m^{-2}$ ) at Indian Head in 2003 (Table 3.7). However, due to the low wild oat densities encountered at the Indian Head site in 2003, maximum wild oat seed production was likely underestimated, as evidenced by high wild



**FIGURE 3.3** Wild oat seed production predicted as a function of wild oat density and relative time of emergence at (A) Indian Head 2002, (B) Indian Head 2003, (C) Kernen 2003. Predicted values are represented by lines on the response surface and are the result of fitting the data to Equation 3.5:  $S_d = aD / [(e^{CT}) + aD/B]$ . Parameter estimates are shown in Table 3.7. Points (●) represent observed values with open points (○) indicating observed values below the transparent response surface.

**TABLE 3.7** Parameter estimates ( $\pm$  S.E.) for the wild oat seed production model based on Equation 3.5 using growing degree days.

Location	Year	Parameter Estimates <sup>†</sup>			$R^2$
		$a$	$B_{\ddagger}^{\dagger}$	$C_{\ddagger}^{\dagger}$	
		no. m <sup>-2</sup>	no. m <sup>-2</sup>		
Indian Head	2002	56.5 (7.39)	18 400 (3950)a	0.0078 (0.0014)b	0.75
Indian Head	2003	60.4 (9.98)	7 820 (1050)b	0.0131 (0.0020)a	0.75
Kernen	2003	82.7 (10.9)	29 020 (7150)a	0.0116 (0.0015)a	0.82
Pooled Model§	—	65.6 (6.06)	18 080 (2790)	0.0078 (0.0009)	0.71

<sup>†</sup>  $a$  is the wild oat seed production per unit wild oat as wild oat density approaches 0,  $B$  is the estimated maximum wild oat seed production at high weed densities, and  $C$  is the rate at which  $a$  declines exponentially as relative time of wild oat emergence increases.

<sup>‡</sup> Means within the same column followed by the same lowercase letter are not significantly different ( $P < 0.05$ ).

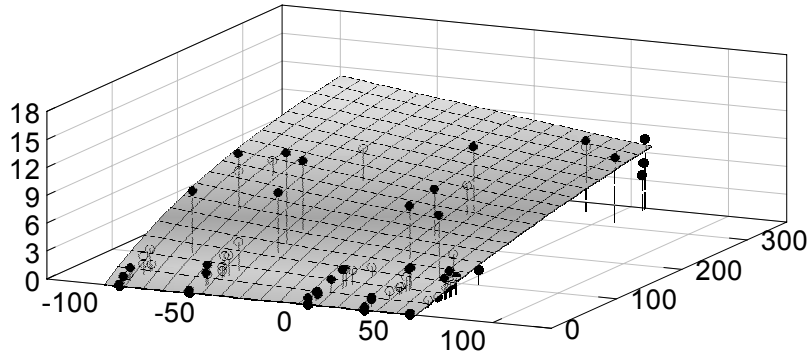
§ Data combined using no. wild oat seed produced m<sup>-2</sup>.

oat seed production per plant yet low seed production  $\text{m}^{-2}$ . Maximum seed production was significantly higher ( $P < 0.05$ ) at Indian Head (2002) and KCRF (2003) than at Indian Head in 2003. O'Donovan et al. (1999) also noted that wild oat seed production varied considerably among years as a function of wild oat density. Parameter  $C$  also varied significantly ( $P < 0.05$ ) among site-years, indicating that relative time of wild oat emergence has a variable effect on wild oat seed production among years and locations (Table 3.7). Although the differences were statistically significant they were once again small and of little importance. Nevertheless, lower  $C$  values at Indian Head (2002) imply that relative time of wild oat emergence affected wild oat seed production less at Indian Head in 2002 than at both sites in 2003. The relatively cool and moist spring conditions experienced at Indian Head in 2002 may have produced more competitive wild oat plants less sensitive to time of emergence (Table 3.2). Wild oat biomass and reproductive output are known to be highest under cool conditions with considerable spring soil moisture (Sharma and Vanden Born, 1978; Rolston, 1981; O'Donovan et al., 1999). However, estimated wild oat seed production per plant at low wild oat densities, parameter  $a$ , was 31% lower at Indian Head in 2002 than at both sites in 2003, but did not vary significantly ( $P < 0.05$ ) among site-years. Wild oat seed production has been shown to increase considerably when seedling emergence precedes crop emergence (Peters and Wilson, 1983). Wild oat produced 68, 41, and 19 seeds per plant when wild oat emergence occurred before, simultaneously, and following (1-2 leaf stage) barley emergence (Peters and Wilson 1983).

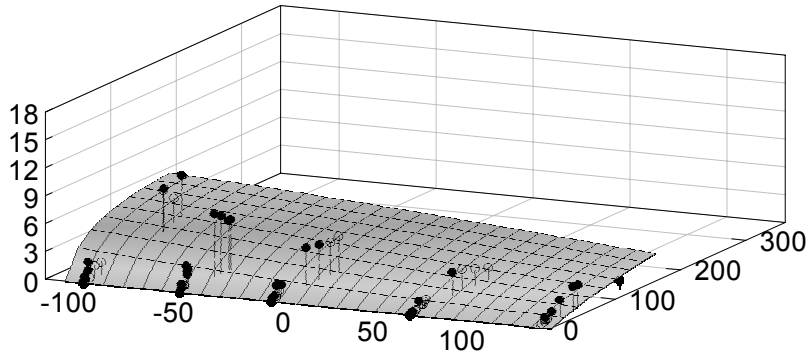
Wild oat contamination, or the percentage of wild oat in the harvested grain sample, varied considerably ( $P < 0.05$ ) among site-years, time of wild oat seedling emergence, and wild oat densities (Figure 3.4). Results were similar to those observed for wild oat seed production (Table 3.8). In all three site-years, wild oat contamination was higher when wild oat emergence preceded crop emergence compared to when wild oat emergence followed crop emergence (Figure 3.4). Increasing wild oat density also increased the percentage of wild oat in harvested grain samples. Wild oat contamination reached levels as high as 14% for early emerging, high densities of wild oat (Figure 3.4C). Because the maximum allowable wild oat contamination in the oat grain

Wild oat seed contamination (%)

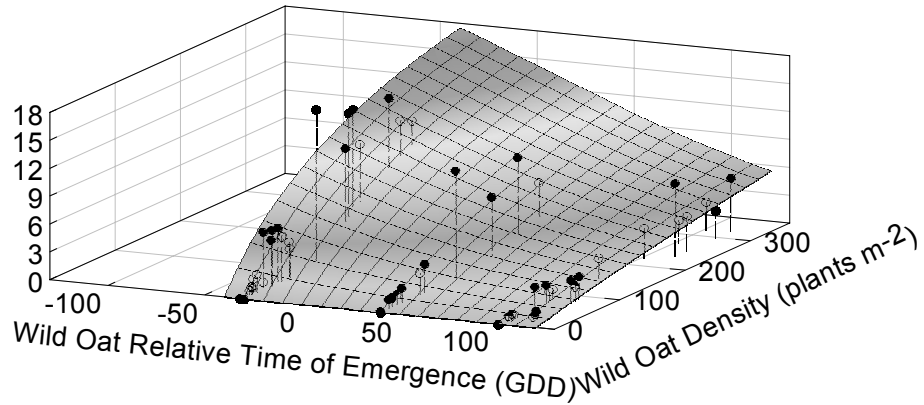
### A. Indian Head 2002



### B. Indian Head 2003



### C. Kernen 2003



**FIGURE 3.4** Wild oat seed contamination predicted as a function of wild oat density and relative time of emergence at (A) Indian Head 2002, (B) Indian Head 2003, (C) Kernen 2003. Predicted values are represented by lines on the response surface and are the result of fitting the data to Equation 3.6:  $P_{wo} = pD/[(e^{CT}) + pD/B]$ . Parameter estimates are shown in Table 3.8. Points (●) represent observed values with open points (○) indicating observed values below the transparent response surface.

**TABLE 3.8** Parameter estimates ( $\pm$  S.E.) for the wild oat contamination model (percentage wild oat in the harvested oat grain sample) based on Equation 3.6 using degree days.

Location	Year	Parameter Estimates†				$R^2$
		$p^\ddagger$	$B^\ddagger$	$C^\ddagger$		
		%	%			
Indian Head	2002	0.0389 (0.0050)b	20.0 (6.3)a	0.00553 (0.0011)b		0.78
Indian Head	2003	0.0874 (0.0111)a	7.9 (1.0)b	0.00814 (0.0014)ab		0.78
Kernen	2003	0.0833 (0.0115)a	26.9 (6.9)a	0.01250 (0.0017)a		0.79
Pooled Model§	—	0.0618 (0.0065)	15.8 (2.7)	0.00668 (0.0010)		0.66

†  $p$  is the wild oat contamination as per unit wild oat density approaches 0,  $B$  is the estimated maximum wild oat contamination at high wild oat densities, and  $C$  is the rate at which  $p$  declines exponentially as relative time of wild oat emergence increases.

‡ Means within the same column followed by the same lowercase letter are not significantly different ( $P < 0.05$ ).

§ Data combined using no. percentage wild oat in the harvested oat grain sample.

sample is only 1%, the implications of wild oat time of emergence and density on oat quality are of considerable importance. Ensuring that crop emergence precedes wild oat emergence is critical to reduce wild oat contamination. For example, at KCRF in 2003, 10 wild oat plants  $\text{m}^{-2}$  emerging 29 GDD before the crop would result in 1% contamination (Figure 3.4C). However, it would take 60 wild oat seedlings  $\text{m}^{-2}$  emerging 111 GDD after the crop to cause that same 1% contamination. In addition, because wild oat typically matures slightly earlier than oat, delaying harvest would allow most of the wild oat seed to fall to the ground, thereby reducing wild oat contamination in the oat.

The high degree of similarity between Figures 3.3 and 3.4 suggests a strong relationship between wild oat seed production and contamination at both sites in 2003. However, this was not the case at Indian Head in 2002. The relationship between time of emergence and density in influencing wild oat contamination was less asymptotic than for wild oat seed production at Indian Head in 2002 (Figures 3.3A and 3.4A). This was likely due to wild oat seed shattering in the first two emergence dates. Consequently, time of emergence was expected to have less effect on contamination in this site-year, but values for the  $C$  parameter were similar at Indian Head in 2002 for both variables (Table 3.8). Furthermore, predictions of wild oat seed shed at harvest based on the seed shed, growing degree day model developed by Shirtliffe et al. (2000) revealed that seed shed at the first emergence date was probably lower at Indian Head in 2002 (60%) than at KCRF (74%) in 2003 (Table 3.9). I suspect that lower contamination rates at the Indian Head (2002) site may have resulted from several factors. First, estimated wild oat seed production per plant was lowest at Indian Head in 2002 (Table 3.7). Second, because the percentage of wild oat contamination is determined from the oat grain sample on a weight basis, it is highly dependent on oat yield and wild oat seed size. Although earlier emerging wild oat produced more seed (Figure 3.3), these seeds were likely smaller than those produced on later emerging plants. In addition, oat yield was higher at Indian Head in 2002, essentially diluting the concentration of wild oat seed in the grain sample. Third, frequent rainfall events in late August likely caused preharvest dehiscence of *A. fatua* seeds (Table 3.2), which cannot be accounted for in Shirtliffe et al.'s (2000) model. Nonetheless, time of emergence strongly influenced the percentage of wild oat in the



harvested oat grain sample, even where substantial seed shattering may have occurred (Figure 3.4A).

#### **3.3.4 Effects of wild oat relative time of seedling emergence and density on oat quality**

Increasing wild oat density caused a significant ( $P < 0.05$ ) linear reduction in oat TKW for all site-years (Table 3.10). Although statistically significant, average oat TKW was only 4% lower at 320 plants  $\text{m}^{-2}$  than in wild oat-free controls. Furthermore, no differences were observed in oat TKW between density treatments up to 80 wild oat plants  $\text{m}^{-2}$  in two of three site-years. Thus, the observed differences are likely not agronomically important. Time of wild oat seedling emergence did not significantly affect ( $P < 0.05$ ) oat TKW for any site-year.

Oat test weight was generally unaffected by wild oat density ( $P < 0.05$ ), the exception being Indian Head 2003 (Table 3.10). Test weight from oat growing at this site at a wild oat density of 320 wild oat plants  $\text{m}^{-2}$  were slightly higher than at lower wild oat densities. I am unable to offer an explanation as to the cause of this response. Test weight was not significantly affected ( $P < 0.05$ ) by time of wild oat seedling emergence for any site-year.

My results agree well with those of Wildeman (2004) and Manthey et al. (1996). In 3 of 4 site-years, Wildeman (2004) found no effect of wild oat density on oat TKW or test weight. Similarly, Manthey et al. (1996) demonstrated that oat test weight, 500-kernel weight, and groat percentage were unaffected by kochia (*Kochia scoparia* L.) density. Barley thousand kernel weight was 3.7% lower when grown with a target wild oat density of 250 plants  $\text{m}^{-2}$  compared with wild oat-free controls (O'Donovan et al., 1999). However, wild oat densities in agricultural fields are typically much lower than those in the previous studies. In a recent survey conducted in Saskatchewan, wild oat occurred on approximately 51% of fields at an average density of 7 plants  $\text{m}^{-2}$  (Leeson et al. 2003).

**TABLE 3.9** Estimated percentages of wild oat seed remaining on the plant at the various wild oat emergence dates based on accumulated growing degree days after emergence.

Location †	Year	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
		Seed Date	Seed Date	Seed Date	Seed Date	Seed Date
		%				
Indian Head	2002	40.4‡	53.3	74.5	78.6	83.7
Indian Head	2003	41.6	59.5	75.4	88.0	95.2
Kernen	2003	26.0	37.7	73.9	84.9	85.2

† Harvest dates: Indian Head 2002 – September 5; Indian Head and Kernen 2003 – August 20.

‡ Estimates calculated based on log-logistic equation:  $Y = 9.47 + [(100-9.47)/ 1 + \exp^{0.0164(GDD - 1549)}]$  Shirliffe et al. (2000).

**TABLE 3.10** Oat thousand kernel weight, test weight, percentage thin and plump kernel responses to wild oat relative time of emergence and density at three site-years.

Effect	Thousand Kernel Weight (g)			Test Weight † (kg hl <sup>-1</sup> )			Thin Kernels (%)			Plump Kernels (%)		
	IH 02‡	IH 03§	KCRF 03¶	IH 02	IH 03	KCRF 03	IH 02	IH 03	KCRF 03	IH 02	IH 03	KCRF 03
Density # (plants m <sup>-2</sup> )												
0	39.4	37.6	36.9	50.2	49.6	50.7	2.40	4.44	-††	-	81.1	-
20	38.0	37.5	36.9	50.3	49.3	50.7	2.41	4.77	-	-	79.5	-
80	37.9	37.4	36.4	50.1	49.5	50.6	2.74	4.84	-	-	79.8	-
320	36.5	36.5	36.1	50.7	50.0	50.9	3.26	5.25	-	-	77.9	-
LSD <sub>0.05</sub>	1.0	0.6	0.7	NS	0.4	NS	0.38	0.43	-	-	1.8	-
Linear ‡‡	***	**	*	*	***	NS	***	**	-	-	*	-
Emergence Time # (GDD)												
-100	37.6	37.3	36.9	50.3	49.7	50.6	2.90	5.07	-††	-	79.8	-
-50	37.2	36.9	36.4	50.0	49.6	50.8	3.01	5.12	-	-	80.4	-
0	38.2	37.1	36.6	50.2	49.6	50.7	2.86	4.71	-	-	78.1	-
50	38.2	37.5	36.3	50.5	49.7	50.9	2.47	4.69	-	-	78.5	-
100	38.5	37.6	36.7	50.6	49.4	50.7	2.28	4.45	-	-	81.3	-
LSD <sub>0.05</sub>	NS	NS	NS	NS	NS	NS	0.43	0.48	-	-	2.0	-
Linear ‡‡	NS	*	NS	*	NS	NS	**	***	-	-	NS	-

† Multiply value by 10 to obtain test weight as kg m<sup>-3</sup>.

‡ IH 02, Indian Head 2002.

§ IH 03, Indian Head 2003.

¶ KRF 03, Kernen Crop Research Farm, Saskatoon, 2003.

# Significance of values within a column determined by protected  $\text{LSD}_{0.05}$ .

†† Means presented in Table 3 due to significant wild oat density  $\times$  time of emergence interaction.

‡‡ Significance of contrasts for linear effects: NS = not significant; \*, \*\*, \*\*\*, significant  $P < 0.05$ ,  $P < 0.01$ ,  $P < 0.001$ , respectively.

Thus, my suggestion is that wild oat density will have minimal impact on oat thousand kernel weight and test weight. Furthermore, even where statistical differences were detected in this study, they were generally small and would be of little economic consequence.

Wild oat relative time of emergence and density significantly ( $P < 0.05$ ) affected the percentage of plump and thin kernels in all site years (Table 3.10). Significant linear effects of wild oat density on oat plump and thin kernel percentages were observed at Indian Head in 2003 and at Indian Head in 2002 and 2003, respectively. In contrast, only thin kernel percentage at Indian Head (2002 and 2003) demonstrated a linear response to wild oat time of emergence (Table 3.10). Nevertheless, in both years at Indian Head, a significantly lower percentage of thin kernels (0.6%) were present in the grain sample when wild oat emerged subsequent to oat (50 and 100 GDD) compared with emergence prior to the crop (Table 3.10). Similarly, an increase in target wild oat density to 320 plants  $\text{m}^{-2}$  corresponded to a 0.8% increase in percentage thin kernels versus the wild oat-free treatment at Indian Head in both years (Table 3.10). Averaged over wild oat density and time of emergence treatments, the percentage thin kernels was greater at Indian Head in 2003 than 2002. The large percentage thin kernels at Indian Head 2003 was likely a consequence of reduced moisture levels and substantial competition from wild oat during grain filling (Table 3.2). Limited moisture availability frequently results in reduced seed set and filling stemming from reduced leaf area, photosynthesis, and assimilate transfer (Passioura 1994).

The percentage of plump oat kernels was also affected by wild oat density and relative time of emergence at Indian Head 2003 (Table 3.10). Increasing wild oat density from the wild oat-free control to 80 and 320 plants  $\text{m}^{-2}$  resulted in 1.6% and 3.2% reductions in the percentage plump kernels, respectively. Plump kernel percentage was generally affected little by relative time of wild oat emergence, with differences between wild oat emergence before oat and wild oat emergence after oat being minimal and non-significant in most cases. Nonetheless, the percentage of plump kernels was slightly higher when wild oat emergence followed oat versus simultaneous emergence of the two species (Table 3.10).

An interaction between wild oat density and relative time of emergence resulted in KCRF 2003 thin and plump kernel data (Table 3.11) and Indian Head 2002 plump kernel data (data not shown) being analyzed within density. At both sites, the percentage of plump kernels decreased with increasing wild oat density and earlier wild oat emergence, while the opposite was noted for KCRF 2003 thin kernel percentage. However, percentage thin or plump kernels were only significantly affected by relative time of wild oat emergence at wild oat high densities in both cases. At KCRF 2003, some 2% fewer thin and 10% more plump kernels were observed when a target wild oat density of 320 plants m<sup>-2</sup> emerged 100 GDD after oat versus 100 GDD before oat emergence.

Both percentage plump and thin kernels appear to be minimally affected by wild oat density and relative time of emergence, regardless of the sizeable yield losses (as high as 70%) incurred under wild oat competition reported earlier (Figure 3.1). Increasing weed competition has previously been shown to reduce crop yields without affecting crop quality (Bell and Nalewaja 1968; Manthey et al. 1996; Wildeman 2004). Wildeman (2004) noted that significant, but small increases in thin kernels were observed with increasing wild oat densities, despite large yield reductions. Increasing kochia densities reduced crop yield but did not affect the groat percentage, groat ash, starch, lipid, or protein content of oat grown in North Dakota (Manthey et al., 1996). Similarly, Bell and Nalewaja (1968) indicated that despite considerable yield loss, no reduction in wheat and barley protein concentration or kernel size occurred under competition from wild oat at a density of 191 plants m<sup>-2</sup>.

### **3.3.5 Management implications**

The results of this study clearly indicate that wild oat time of emergence relative to oat was crucial in determining the outcome of wild oat-oat competition. My results emphasize the importance of applying control measures to reduce the competitive effects of early emerging wild oat, thereby minimizing oat yield and quality losses, as well as reducing wild oat seed production to minimize long-term seedbank changes. High

**TABLE 3.11** Response of percentage thin and plump grains to wild oat density by time of emergence interaction for data collected at the Kernen in 2003.

Density (plants m <sup>-2</sup> )	Thin Kernels (%)				Plump Kernels (%)			
	0	20	80	320	0	20	80	320
Emergence time (GDD) †								
-100	3.29	3.36	3.82	7.09	79.4	80.8	80.6	72.4
-50	3.03	3.24	4.28	5.03	80.7	80.2	77.0	76.5
0	3.74	3.71	3.64	4.28	79.3	80.0	78.3	71.2
50	3.40	3.83	3.81	4.07	81.3	76.5	78.3	82.5
100	3.67	3.14	3.82	4.74	83.7	84.5	77.6	82.3
LSD	NS	NS	NS	1.89	NS	NS	NS	6.57

† Significance of values within a column (wild oat density) determined by protected LSD<sub>0.05</sub>.

densities of early emerging wild oat greatly reduced oat yield and quality (Figures 3.1 and 3.4). Observed oat yield loss and wild oat contamination were as high as 70% and 15%, respectively (Figures 3.1 and 3.4). Despite varying among site-years, the effect of relative time of wild oat emergence (*C* parameter) exhibited little variation in absolute values within site-years for oat yield loss, wild oat seed production, and wild oat contamination. This suggests that relative time of wild oat emergence influences these variables similarly.

The results also emphasize the importance of a non-selective herbicide application prior to crop emergence to reduce the negative effects of wild oat competition on oat yield by ensuring that crop emergence precedes wild oat emergence. Nevertheless, given that large yield and quality (wild oat contamination) reductions were observed in this study, and that no chemical control for wild oat in oat exists, it is likely that selecting for earlier emerging oat would prove a valuable selection criterion in oat breeding programs. According to my data, oat emerging even 20 GDD earlier than wild oat would reduce yield loss from 24% to 21% at a wild oat density of 80 plants m<sup>-2</sup>. Because germination and emergence can vary by 15 and 16 GDD between western Canadian wheat and barley cultivars, respectively (Lafond and Baker, 1986a; Juskiw and Helm, 2003), potential may exist to breed for earlier emergence in oat. Nevertheless, these seemingly small differences in emergence time can contribute to important reductions in yield loss and thus, it is recommended that more emphasis be placed on selecting for early emerging, more competitive oat in breeding programs.

Although wild oat density and time of emergence significantly reduced oat plump kernel percentage and TKW, reductions were minimal and would not result in grade reductions. Test weight, the most commonly used method to assess oat quality (Forsberg and Reeves 1992), was generally unaffected by wild oat time of emergence and density and values were consistently above the 47 kg/hl minimum and the 49 kg/hl level required for price premiums established by the milling industry (Quaker Oats Company of Canada, 2003). Furthermore, despite significant increases in thin kernel percentages, the largest observed increase was only 2-7%. Since oat millers tolerate up to 10% thin kernels (Quaker Oats Company of Canada, 2003), the increases observed in this study



would be biologically and economically insignificant. However, these increases could be problematic in environmental conditions more conducive to wild oat growth. Both TKW and plump kernel percentage were slightly affected by wild oat density, but were generally not influenced by time of wild oat emergence. Nevertheless, because these measures are indirectly reflected in test weight and percent thin kernels, oat millers do not place restrictions on them. Therefore, wild oat time of emergence and density have relatively unimportant effects on oat physical grain quality and oat producers should not implement measures to control wild oat based on the potential reductions in oat plump kernel percentage, TKW, and test weight that may be incurred from the weed. Much greater attention should be given to minimizing reductions in oat quality resulting from cultural practices (May et al., 2004) and environmental effects (Doehlert et al., 2001).

This is the first study to base relative time of weed emergence on thermal time rather than Julian date or crop stage. Planting and analyzing on a GDD basis provides a number of advantages to relative time of emergence studies. First, it homogenizes planting dates by accounting for differences in biological activity based on air temperature. Although germination occurs in the soil, access to soil temperature data is often limited or not possible. However, soil and air temperature are known to be positively correlated, particularly in clay soils (Chang, 1968). Time of emergence studies have been traditionally conducted based on planting weeds at specific Julian dates (O'Donovan et al., 1985; Knezevic and Horak, 1998) or to emerge at various crop stages (Chikoye et al., 1995; Dieleman et al., 1995; Bosnic and Swanton, 1997), rather than planting based on thermal time and may have thus provided less accurate estimations of the actual relationship between relative time of weed emergence and crop yield loss. My method allows for uniform as well as adequate intervals between emergence treatments, resulting in more accurate predictions of crop yield losses over a wide range of emergence times. This method also allows for direct comparisons between multiple studies, providing the opportunity for inferences to be drawn among various crop and weed species combinations. Finally, it allows for easy estimation and calculation of yield loss values in the field over a wide range of emergence times. If the exact emergence time of a weed relative to the crop is not known, estimations can be provided based on the high degree of

correlation between crop and weed growth stages (Weaver, 2003). For example, 80 wild oat plants  $\text{m}^{-2}$  in the 3-leaf stage occurring in a 4-leaf oat crop (220 plants  $\text{m}^{-2}$ ) probably emerged between 90 to 100 GDD after the crop based on wild oat and oat phyllochron intervals of 92 GDD and 94 GDD, respectively (Shirtliffe et al. 2000; Chapter 4).

The results of this study can be incorporated into calculations and used in the development of economic decision rules for managing wild oat in oat. For instance, although oat yield losses from early emerging wild oat were substantially greater than those from wild oat that emerged after the crop, early emerging wild oat can be controlled with a non-selective herbicide application prior to crop emergence. In contrast, wild oat that emerges subsequent to the crop cannot be controlled with a herbicide and thus, removal of both the crop and weed followed by reseeding is the only method of weed control in this situation. However, it is known that delayed seeding of oat also results in appreciable reductions in yield and quality (May et al., 2004). Therefore, a decision rules based model is needed to assist oat growers in making informed decisions regarding the management of wild oat in oat. The yield loss values obtained in this study will prove useful in the development of such a model.

## **4.0 Oat caryopsis size and genotype effects on wild oat – oat competition**

### **4.1 Introduction**

In most cereal crops, selective control of wild oat is achieved with a variety of herbicides. However, because of the genetic similarity of tame and wild oat, no herbicides exist to selectively remove the weed from the crop. Therefore, reliance on cultural weed control is central to successful wild oat management in oat. Traditionally, wild oat was controlled by delaying planting so that emerged wild oats could be controlled by tillage (May et al., 2004). However, delayed planting of oat causes substantial declines in grain yield, test weight, plump seed, and groat percentage with a corresponding increase in thin seed percentage (Nass et al., 1975; Ciha, 1983; May et al., 2004). Consequently, alternative methods are required to manage wild oat in oat.

Seed size may be an important determinant of crop competitive ability. Although large seed generally appears to produce larger, more vigorous seedlings than small seed (Kaufmann and McFadden, 1963; Kaufmann and Guitard, 1967; Lafond and Baker, 1986b), the effects of seed size on germination and emergence characteristics are inconsistent. Large wheat seeds were found to have a slower germination rate than small seeds at several temperature and osmotic potential combinations (Lafond and Baker, 1986a). In contrast, Kawade et al. (1987) and Andersson (1996) observed increased germination and emergence from large seed of pearl millet (*Pennisetum glaucum* L.) and narrowleaf hawksbeard (*Crepis tectorum* L.), respectively.

The relationship between seed size and yield, like that of germination, also appears to be somewhat ambiguous within and among cultivars. Emergence, head number, and grain yield among soft red winter wheat cultivars in Illinois were not affected by seed size (Mian and Nafziger, 1992). In fact, crops grown from small seed yielded more than large seed in some years. Dhillon and Kler (1976) also noted that plants established from small-seeded soybean varieties (*Glycine max* L. Merr.) yielded more compared to those established from large-seeded varieties. Alternatively, within cultivars, small seed of winter wheat, spring wheat, and oat yielded 81, 82, and 83% as much as large, respectively (Kiesselbach, 1924). Likewise, yield from large barley seed was 11% greater than the yield produced from small seed averaged among cultivars (Demirlicakmak et al., 1963).

The contribution of seed size to crop growth and development may be enhanced under competition with weeds. Xue and Stougaard (2002) found that spring wheat competitiveness with wild oat increased as seed size and seeding rate increased. Seeding large seed reduced wild oat tillering by 15%, and biomass and seed production by 25%. Moreover, wheat yield increased 18% with the use of larger seed in the presence of wild oat competition (Stougaard and Xue, 2004). Thus it appears seed size may reduce wild oat growth and fecundity and as such, minimize the adverse effects of wild oat competition on crop yield and quality. However, their study included various seed sizes of only one genotype, limiting the conclusions that can be drawn as the effects of seed size may vary within genotypes.

Unfortunately, little effort has been directed towards improving the ability of oat to compete with wild oat. Furthermore, studies comparing seed size effects among various oat genotypes in response to weed competition are lacking and thus, recommendations must be limited. The main objective of this study was to assess the relative importance of oat caryopsis size and genotype in affecting wild oat – oat competition in the greenhouse. Genotypes were included in the study to ascertain whether caryopsis size effects were consistent or variable among genotypes. I hypothesize that the effects of caryopsis size will be genotype-dependent, and will be enhanced with wild oat competition. Because I anticipate a small response to caryopsis size, the ability of greenhouse studies to

minimize extrinsic variability and provide sufficient resources for optimal plant growth was appealing. This allowed the effects on competition of genotype and caryopsis size to be explored with all other variables held constant and avoided having to speculate on the impact of various abiotic and biotic stresses that frequently confound results from field experiments.

## **4.2 Materials and Methods**

### **4.2.1 Experimental Design and Location**

A greenhouse experiment was conducted at the University of Saskatchewan at Saskatoon, SK, Canada from September to December, 2002 and October to December, 2003. A 3-way factorial randomized complete block design with three oat genotypes, three caryopsis (dehulled kernel) sizes, two wild oat densities, and four replicates was utilized. Oat genotypes evaluated were AC Assiniboia, CDC Boyer, and CDC Orrin. Caryopsis size classes were established consisting of small (groat weight = 15 mg), medium (groat weight = 25 mg), and large (groat weight = 35 mg) caryopses of each genotype that possessed proportionately equal groat sizes (based on groat weights) within caryopsis size classes. In other words, large seeds of each genotype had similar groat weights, even though they may have been physically bigger (due to different hull content) and thus were retained on a different sieve when sized. Oat was grown either with wild oat competition at a target wild oat density of 225 plants m<sup>-2</sup> or without wild oat competition (monoculture).

### **4.2.2 Caryopsis size classification**

Seeds of each genotype were obtained from common seed increases at the time of harvest in 2002 from the Crop Development Center at Saskatoon, Saskatchewan, Canada. All seed used was obtained from the same location and year and was thus exposed to the same environmental conditions. Due to the hulled seed structure of *Avena sativa*, a series of fractionation tests were conducted where seeds of each genotype were fractionated into

several proportions using numbers 7 through 5 sieves (Can-Seed Equipment Ltd., Saskatoon, SK, Canada), ranging in size from 1.95- x 8.33-mm to 2.75- x 8.33-mm. Subsequent to fractionation the variability in seed size distributions, thousand kernel weight (TKW), test weight, and thousand groat weight between and among these seedlots were determined.

To eliminate differences in hull content between genotypes, caryopsis size classifications (small, medium, and large) were derived based on groat weight. The required TKWs needed to obtain the desired caryopsis size classes were determined and chosen based on regressions of thousand kernel weight vs. thousand groat weight. Seedlots of each genotype were then separated into size classes and from those fractions containing the seeds that were the size of the predetermined groat size classes (small 14 to 16 mg, medium 24 to 26 mg, and large 34 to 36 mg), seedlots of 200 caryopses each were counted and removed. Each 200 caryopses seedlot was then placed on a scale and the largest or smallest seeds were removed and replaced by medium size seeds of the respective size fraction, one at a time, until the final weight was equal to 200 times the target seed weight of the caryopsis size class of the genotype. Caryopsis weights, corresponding groat weights and regression results are shown in Table 4.1. Wild oat seed used in the study consisted of those retained on a 1.95- x 8.33-mm sieve.

#### **4.2.3 Experimental procedures**

Ready Earth<sup>®</sup> (W.R. Grace and Co. Ltd., ON., Canada), a vermiculite, soil-less mix, was added to each of 100, 20 cm diameter pots. All pots were watered to field capacity and lined with a coffee filter to aid in growth media retention. A circular pot-planter, 18 cm in diameter, was constructed to ensure uniform seeding depth and spacing between plants. Whole seeds were planted on October 8 (2002) and September 29 (2003) in a square arrangement at 3.8 cm intervals and at a depth of 3 cm. Eight oat caryopses per wild oat-free treatment (caryopsis size within genotype) were sown in each of the eight holes per pot to achieve a target density of 225 plants m<sup>-2</sup>. Pots with a wild oat competition treatment were sown with an additional eight wild oat at target density of

**TABLE 4.1** Thousand kernel weight, thousand groat weight, and  $R^2$  for the regression of the various caryopsis size classes and genotypes used in the study.

Caryopsis Size	Thousand Kernel Weight (g)			Thousand Groat Weight (g)			$R^2$
	Small	Medium	Large	Small	Medium	Large	
Genotype†							
AC Assiniboia	24.5 (7)	34.9 (12)	46.0 (38)	15.27	24.87	34.74	0.99‡
CDC Boyer	23.9 (8)	35.2 (26)	46.3 (33)	15.34	25.07	34.58	0.99§
CDC Orrin	22.5 (4)	35.3 (18)	47.3 (26)	14.83	25.21	35.01	0.99¶

† Values based on regressions of thousand kernel weight vs. thousand groat weight for each genotype. Values in parentheses indicate the percentage of each size class within the total seedlot as determined by fractionation (see caryopsis size classification).

‡  $R^2$  for regression between thousand kernel weight and thousand groat weight within genotype AC Assiniboia. Regression equation:  $Y = 1.12x + 7.13$ .

§  $R^2$  for regression between thousand kernel weight and thousand groat weight within genotype CDC Boyer. Regression equation:  $Y = 1.17x + 5.75$ .

¶  $R^2$  for regression between thousand kernel weight and thousand groat weight within genotype CDC Orrin. Regression equation:  $Y = 1.22x + 4.56$ .

225 plants m<sup>-2</sup>. In addition, 16 pots were sown to wild oat to act as border pots, minimizing edge effects. Where final emergence was less than targeted, plants were replaced by transplantation with simultaneously growing plants of the same treatment. This ensured all pots contained equidistant, equiangular, equal densities of each species at uniform growth stages. All pots were covered with 2 cm of dry potting mixture and slightly compacted. Pots were rotated to new positions every four days to minimize environmental variability and border effects within the experiment.

All pots were watered to field capacity as needed until the flag leaf stage after which watering occurred bi-daily. Water soluble fertilizer (20-20-20) was applied evenly to pots once weekly until the flag leaf stage after which it was applied bi-weekly. Emergence monitoring was conducted by recording the number of seedlings emerging above the soil surface three times daily (0700, 1400, and 2000 h). Wild oat was distinguished from oat by the use of a spatial planting arrangement, which also ensured that each plant of either species was bordered on all sides by a plant of the other species. Haun (1973) growth stage was recorded bi-weekly on 3 plants per pot until the oat reached the 6-leaf stage beyond which measurements were deemed too destructive. Plants were harvested on the 17<sup>th</sup> and 9<sup>th</sup> of December in 2002 and 2003 respectively, at the Zadok's 80 to 82 stage (Zadoks et al., 1974). Final plant height was determined after wild oat and oat plants were cut at ground level and separated. Tillering (panicles m<sup>-2</sup>) and biomass were recorded in both years, while seed output (seeds per panicle and seeds m<sup>-2</sup>) could only be quantified in 2002 due to unintended damaging insecticide drift from a nearby experiment in 2003, which resulted in premature necrosis and chlorosis of the penultimate and flag leaves, as well as abortion of some spikelets. Seed production was estimated on 5 panicles per pot by counting the number of fertile spikelets and then multiplying by two as wild oat typically have 2-3 caryopses per spikelet (Sharma and Vanden Born, 1978). Plants of both species were subsequently dried for 96 h at 40°C to determine shoot biomass.



#### 4.2.4 Statistical analysis

With the exception of oat emergence data, all data for each species were subjected to a three-way (genotype \* seed size \* wild oat density) factorial analysis of variance using the mixed model procedure of SAS (PROC MIXED; Littell et al., 1996), with degrees of freedom calculated by Satterthwaite's approximation method. Within the mixed procedure, the log likelihood ratio was employed to test the significance of the random effect of year and its interactions with genotype, caryopsis size, and wild oat competition (Littell et al., 1996). This test indicated data could be combined over years for the analysis of variance and regression procedures. Fixed effects and random variance components were estimated by restricted maximum likelihood (REML), which estimates treatment effects by least squares and then calculates the likelihood function of the residuals (Steele et al., 1997). Genotype, caryopsis size, and wild oat density were considered fixed effects whereas blocks, years, and their interactions with fixed effects were considered random effects. All residuals were initially tested for normality with the UNIVARIATE procedure in SAS (SAS Institute Inc., 1996). To satisfy the assumptions of ANOVA, oat panicles m<sup>-2</sup>, seeds per panicle, and wild oat biomass were log (base 10) transformed. Transformation generally improved or normalized the residuals in these cases and thus, analysis of variance was performed on transformed data.

Haun (1973) growth stage data were regressed against GDD accumulated from emergence using PROC REG (SAS Inst., 1996), with the slope taken as the phyllochron interval in GDD (Juskiw et al., 2001). GDD were calculated using the following equation:

$$GDD = \sum \left[ \left( \frac{T_{max} + T_{min}}{2} \right) - T_{base} \right] \quad [4.1]$$

where  $T_{max}$  is the daily maximum air temperature,  $T_{min}$  is the daily minimum temperature, and  $T_{base}$  is the base temperature (0 C) for growth. Phyllochron intervals were then analyzed with the mixed model procedure of SAS (SAS Institute Inc., 1996) as described above. All data were analyzed within wild oat density and genotype as significant interactions demanded. Means were separated using Fisher's protected least significant difference with treatment effects declared significant at  $P < 0.05$ .

Oat median emergence time, or the time to 50% emergence, was described by the fitting the following logistic function to each experimental unit (pot):

$$P_t = 1/[1+e^{-a(t+b)}] \quad [4.2]$$

where  $P_t$  is the proportion of caryopses emerged at time  $t$ ,  $t$  is thermal time in GDD (base temperature = 0 C) accumulated since the initiation of the experiment,  $a$  is the estimated rate of emergence (number of emerged caryopses per GDD), and  $b$  is the estimated median emergence time (GDD) in each experimental unit. Final emergence percentage and median emergence time were then subjected to analysis of variance, combined over years, using PROC MIXED (Littel et al., 1996). Means were again separated using Fisher's protected least significant difference with treatment effects declared significant at  $P < 0.05$ .

### 4.3 Results and Discussion

The main effects of caryopsis size and wild oat competition were significant for oat shoot biomass (Table 4.2). Oat established from large caryopses produced 17% more biomass ( $P < 0.001$ ) than plants derived from small caryopses, irrespective of genotype or wild oat competition (Table 4.3). As expected, competition with wild oat had a large effect on oat shoot biomass. Among genotype and caryopsis size, oat grown in mixture with wild oat produced 54% of the biomass ( $P = 0.05$ ) of oat grown in monoculture (Table 4.3). Although not statistically significant ( $P = 0.09$ ), shoot biomass of *A. sativa* appeared to be affected by genotype (Table 4.2). A consistent trend was observed among genotypes whereby CDC Boyer produced 23% greater biomass than AC Assiniboia and 12% greater biomass than CDC Orrin (Table 4.3).

Main effects for caryopsis size also were significant ( $P = 0.004$ ) for wild oat shoot biomass. Wild oat shoot biomass was approximately 31% lower when competing with oat established from large caryopses compared with small (Table 4.3). Thus, all oat

**TABLE 4.2** Analysis of variance results (*P*- values) for oat median emergence time, final emergence, height, biomass, panicle and seed production as affected by oat genotype, initial caryopsis size, and wild oat competition.

Source	df	Median Emergence		Final Emergence	Phyllochron Interval	Height	Biomass	Panicles	Seeds†	Seeds†
		GDD	Time	%	GDD	cm	g m <sup>-2</sup>	no. m <sup>-2</sup>	no. panicle <sup>-1</sup>	no. m <sup>-2</sup>
Genotype (G)	2	0.286		0.570	0.279	0.322	0.086	0.048*	<0.001***	0.612
Caryopsis Size (S)	2	0.955		0.298	0.500	0.324	<0.001***	<0.001***	0.153	0.611
Wild Oat (WO)	1	0.516		0.786	0.017*	0.214	0.049*	0.110	<0.001***	0.107
G X S	4	0.583		0.733	0.515	0.439	0.827	0.450	0.599	0.654
G X WO	2	0.924		0.584	0.222	0.805	0.955	0.966	0.215	0.666
S X WO	2	0.085*		0.023*	0.182	0.293	0.229	0.530	0.642	0.671
G X S X WO	4	0.104		0.706	0.554	0.050*	0.676	0.774	0.637	0.754
Run (R)	1	0.277		0.430	0.247	0.309	0.282	0.267	-	-
R X G	2	0.156		0.465	0.258	0.199	0.376	0.426	-	-
R X S	2	0.298		0.283	0.295	0.308	0.243	0.442	-	-
R X WO	1	0.321		0.293	0.283	0.328	0.192	0.291	-	-

† Each value is based on one experimental run in 2002.

\*, \*\*, \*\*\*, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

**TABLE 4.3** Tame oat dry matter, panicle, and seed production and wild oat dry matter and seed production of three tame oat genotypes and caryopsis sizes with or without wild oat competition.

Treatment	Tame Oat Biomass	Tame Oat Panicles	Tame Oat Seeds†	Wild Oat Biomass	Wild Oat Seeds†
	g m <sup>-2</sup>	no. m <sup>-2</sup> ‡	no. panicle <sup>-1</sup> ‡	g m <sup>-2</sup> ‡	no. m <sup>-2</sup>
Genotype§					
AC Assimiboia	2860	2.88 a (760)	1.80 b (63)	3.22 (1660)	48500
CDC Boyer	3510	2.89 a (770)	1.89 a (78)	3.20 (1580)	48500
CDC Orrin	3160	2.82 b (650)	1.91 a (83)	3.24 (1740)	56400
LSD	NS	0.05	0.04	NS	NS
Caryopsis Size§					
Large	3390 a	2.89 a (770)	1.87 (74)	3.16 b (1450)	42400 b
Medium	3250 a	2.87 a (740)	1.89 (77)	3.22 b (1640)	49300 b
Small	2890 b	2.83 b (670)	1.85 (70)	3.28 a (1900)	61700 a
LSD	190	0.02	NS	0.06	12100
Wild Oat§					
0	3860 a	2.91 (812)	1.93 a (86)	-	-
250	2500 b	2.80 (630)	1.81 b (64)	-	-
LSD	1340	NS	0.03	-	-

† Each value is based on one experimental run in 2002.

‡ Data are log (base 10) transformed. Values in parentheses represent means back-transformed to approximate their original value.

§ Means within the same column followed by different letters are significantly different ( $P < 0.05$ ) by LSD within genotype, caryopsis size, or wild oat competition.

genotypes examined in this study that were established from large caryopses not only produced more dry matter both in the presence and absence of wild oat competition, they suppressed wild oat dry matter production. Although genotype affected shoot biomass in oat, genotype did not significantly affect ( $P = 0.34$ ) wild oat shoot biomass production (Table 4.4).

Increasing caryopsis size significantly increased ( $P < 0.001$ ) the number of oat panicles per square meter (Table 4.3). Oat established from large caryopses produced 15% more panicles per square meter than plants established from small. However, oat plants established from large caryopses did not produce more seeds per panicle ( $P = 0.15$ ) or seeds per square meter ( $P = 0.61$ ). Competition with wild oat resulted in substantially ( $P < 0.001$ ) lower seed production (43%) with respect to the number of seeds per panicle (Table 4.3). As expected, genotype significantly affected oat panicles per square meter ( $P = 0.05$ ) and estimated seed per panicle ( $P < 0.001$ ). Although CDC Boyer and AC Assiniboia produced more panicles per square meter than CDC Orrin, CDC Orrin compensated by producing 32% more seed per panicle than the other genotypes (Table 4.3).

Based on one experimental run, wild oat produced 45% more seed ( $P = 0.01$ ) when competing with oat established from small caryopses than when competing with plants established from large caryopses (Tables 4.3 and 4.4). Genotype did not significantly ( $P = 0.32$ ) influence wild oat seed production per square meter (Table 4.4). However, a significant interaction between genotype and caryopsis size was present for wild oat seeds per panicle ( $P = 0.05$ ). Caryopsis size only affected wild oat seed production per panicle when competing with CDC Boyer plants (Table 4.5). Wild oat produced more seed per panicle when competing with CDC Boyer plants established from small and medium caryopses than large (Table 4.5).

Interestingly, the differences observed in oat biomass and tillering could not be attributed to variation in oat emergence. Median emergence time and final emergence percentage were not affected by genotype, caryopsis size, or wild oat competition, although wild oat presence by caryopsis size interactions were significant for both (Table

**TABLE 4.4** Analysis of variance results for wild oat height, biomass, panicle and seed production as affected by oat genotype and initial caryopsis size.

Source	df	Height cm	Biomass g m <sup>-2</sup>	Panicles no. m <sup>-2</sup>	Seeds † no. panicle <sup>-1</sup>	Seeds † no. m <sup>-2</sup>
Genotype (G)	2	0.253	0.342	0.625	0.171	0.318
Caryopsis Size (S)	2	0.251	0.004**	0.298	0.080	0.010**
G X S	4	0.760	0.253	0.076	0.046*	0.065
Run (R)	1	0.244	0.301	0.403	-	-
R X G	2	0.407	0.289	0.498	-	-
R X S	2	0.155	0.382	0.455	-	-

† Each value is based on one experimental run in 2002.

\*, \*\*, \*\*\*, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

**TABLE 4.5** Effects of genotype and caryopsis size on wild oat seed per panicle.

Caryopsis Size	Genotype		
	AC Assiniboia	CDC Boyer †	CDC Orrin
Caryopsis Size	Seeds panicle <sup>-1</sup>		
Large	89	64 b	106
Medium	91	107 a	100
Small	102	99 a	101
LSD	NS	33	NS

† Means within the same column followed by different letters are significantly different ( $P < 0.05$ ) by LSD.

4.2). When interactions were analyzed within wild oat treatments, however, caryopsis size did not significantly affect either median emergence time or final emergence of oat. This was due to large seed having better germination than small when wild oat was absent compared to when wild oat was present. The lack of differences may be due to the hulled structure of *Avena* sp. seeds, but given that this is the first study in a hulled cereal to account for initial differences in hull content between seed sizes and genotypes, no evidence exists to support this hypothesis. Nevertheless, these results are congruent with those obtained in *Rumex* species, where no differences in emergence between large and small seeds appear to exist (Cideciyan and Malloch, 1982; Martinkova et al., 1999).

Similarly, variation in oat biomass and tillering could not be attributed to differences in height. Neither genotype nor caryopsis size influenced oat height in monoculture (Table 4.2). However, with wild oat competition present, AC Assiniboia and CDC Boyer derived from large caryopses grew substantially taller than plants established from small caryopses (Table 4.6). Caryopsis size did not affect plant height of CDC Orrin when competing with wild oat. Neither genotype ( $P = 0.25$ ) nor caryopsis size ( $P = 0.25$ ) affected wild oat height (Table 4.4). Likewise, oat phyllochron intervals did not differ across oat genotype ( $P = 0.28$ ) caryopsis size ( $P = 0.50$ ) (Table 4.2). Therefore, the variability observed in oat height, biomass and tillering were not due to differences in rate of leaf appearance. The rate of leaf appearance rate was 4 GDD longer ( $P = 0.02$ ) when oat was grown in mixture with wild oat compared with monoculture (Table 4.2). Oat plants grown in mixture were shaded by taller wild oat plants and less able to compete for light, likely resulting in a reduced assimilate production and a lower rate of leaf appearance. Gautier and Varlet-Grancher (1996) reported that lowering blue light increased the phyllochron in fescue (*Festuca arundinacea* L.). Likewise, Gauthier (1999) noted an increase in the phyllochron of perennial ryegrass (*Lolium perenne* L.) under reduced photosynthetic photon flux densities.

The results of this study clearly articulate the importance of initial caryopsis size to the outcome of wild oat - oat competition (Tables 4.2, 4.3, 4.4). Under greenhouse conditions, initial caryopsis size exerted substantial effects on oat and wild oat dry matter production and tillering among all genotypes examined, regardless of the presence of



**TABLE 4.6** Effects of genotype and caryopsis size on oat height at with wild oat competition present.

Caryopsis Size	Genotype		
	AC Assiniboia †	CDC Boyer †	CDC Orrin
	cm		
Large	128 a	133 a	130
Medium	121 ab	126 b	132
Small	116 b	130 ab	126
LSD	7.9	4.5	NS

† Means within the same column followed by different letters are significantly different ( $P < 0.05$ ) by LSD.

wild oat competition. Moreover, the lack of interactions between seed size and genotype observed in this study suggests that oat genotype and caryopsis size are additive (or independent) in their effects on wild oat – oat competition (Tables 4.2 and 4.4). Thus, my initial hypothesis that genotype and caryopsis size would interact to affect wild oat – oat competition is rejected on this basis.

In this study, oat exhibited both a competitive effect (ability to suppress competition) and competitive response (ability to better tolerate competition) to wild oat competition. When competing with wild oat, greater biomass and tillering were observed in oat plants established from large caryopses compared with small, indicating a competitive response. Alternatively, wild oat biomass and tillering increased substantially when competing with oat plants derived from small seed, demonstrating a competitive effect. Therefore, increasing caryopsis size resulted in an increased ability to both tolerate and suppress wild oat competition (Table 4.3). Consequently, the data suggests that the ability of oat to tolerate and suppress weed competition is positively correlated with respect to caryopsis size. My results agree with those from earlier field trials with wheat and barley where results also suggested a positive correlation between seed size and yield (Kiesselbach, 1924; Demirlicakmak et al., 1963; Xue and Stougaard, 2002). By contrast, genotype only affected tillering in oat and did not substantially influence wild oat dry matter production (Tables 4.3 and 4.4). Therefore, genotype did not affect the ability of oat to suppress weed growth, although a very limited number of genotypes were used in the study.

Whereas caryopsis size influenced both oat and wild oat biomass and panicle production, genotype only affected oat panicle production (Tables 4.3 and 4.4). On this basis, I contend that the positive effects of caryopsis size on competition between wild oat and oat were greater than were observed for the three genotypes examined (Tables 4.2, 4.3, 4.4). Stougaard and Xue (2004) reported that seed size had a greater effect on spring wheat yield than seeding rate when competing with wild oat. Furthermore, the increased biomass production associated with increased caryopsis size indicates more effective resource capture by plants derived from large caryopses. However, because differences in emergence and phyllochron intervals were not observed across caryopsis

sizes, I speculate that the greater competitive ability of oat plants established from large-seeded material was likely related to greater occupancy of space resulting from greater intrinsic growth rates rather than from a faster rate of leaf expansion. Increased growth rates and early seedling vigor in plants established from large seeds have also been observed in wheat (Lafond and Baker, 1986b) and switchgrass (*Panicum virgatum* L.) (Aiken and Springer, 1995).

With respect to plant competition, the relative severity of root and shoot competition is highly dependent on the adequacy with which soil resources (water and nutrients) are supplied. In this study, adequate supplies of soil resources were given as plants were fertilized and watered to maintain optimal growth. In such situations, light becomes the limiting factor for plant growth and competition for aerial resources (light) is greater than for soil resources (Satorre and Snaydon, 1992). Oat plants established from large-seeded materials were more vigorous and produced plants with greater aboveground biomass (Table 4.3). Consequently, these plants were better able to compete for light and thus gained a competitive advantage. This is supported by the fact that smaller-seeded species typically invest more heavily in root than shoot production because of their higher relative growth rate, which leads them to quickly exhaust their seed supplied nutrients (Maranon and Grubb, 1993).

Although the results reported herein come from greenhouse studies, the data suggest that planting large oat caryopses could increase oat dry matter production and tillering both in the presence or absence of wild oat competition. This will likely translate into increased yield as yield increases from the use of large seeds have generally been due to increased tillering (Kaufmann and McFadden, 1963). Moreover, due to the linear relationship between biomass and seed production (Cousens and Mortimer, 1995), increased biomass production generally translates into greater seed production resulting in increased yield. Thus, potential may exist to use crop competition, via the use of large caryopses, as a component of integrated weed management in oat. Furthermore, increasing caryopsis size increased oat biomass and tillering when grown in monoculture, suggesting that the benefits of using large caryopses may be observed even in the absence of competition from weeds. The lack of differences generally observed in this study

between large and medium caryopses suggests that more competitive oat crops may be planted by simply ensuring small caryopses are removed from the seedlots. This should be easily achieved considering that the small caryopses used in this study should not be present in Certified Seed in Canada. The results of this greenhouse study cannot completely describe the response of wild oat – oat competition to oat caryopsis size and genotype. Therefore, further investigation is needed to examine the response of oat – wild oat competition to oat caryopsis size and genotype under field conditions.

## **5.0 General Discussion**

### **5.1 Wild oat relative time of emergence and density**

Results presented in this thesis suggest that wild oat seedling time of emergence and density are critical to wild oat – oat competition. Wild oat that emerged before oat produced considerably more biomass and seed than wild oat that emerged after the crop (Chapter 3). Consequently, substantial declines in oat yield and quality were observed with early emerging wild oat, particularly at high densities. These findings led to the acceptance of the main hypothesis that early emerging wild oat would be more competitive with oat. Similar trends have been observed in other species including barnyardgrass (*Echinochloa crus-galli* L.) in corn (Bosnic and Swanton, 1997), pigweed (*Amaranthus* spp.) in soybean (Dieleman et al., 1995), and wild oat in wheat and barley (O'Donovan et al., 1985; Cousens et al., 1987).

Earlier emerging wild oat are better able to compete for resources such as soil moisture and nutrients, as well as light and as such, gain a competitive advantage over those species that emerge subsequently. Larger root systems and aboveground shoots are believed to contribute to the competitive advantage observed in early emerging wild oat (Chancellor, 1976; O'Donovan et al., 1985). In addition, earlier emerging wild oat was taller than oat in most cases (data not shown) and was likely better able to compete with oat for light. Wild oat dramatically reduced radiation interception in wheat stands (Barnes et al., 1990).

The second part of my main hypothesis, that it may worthwhile to include time of emergence as a selection criteria in oat breeding programs, could not be confirmed with certainty from the results of this study. Given that large yield and quality reductions

were observed in this study (Chapter 3), and that no chemical control for wild oat in oat exists, selecting for earlier emerging oat may prove a valuable selection criterion in oat breeding programs. Results presented in this thesis suggest that even small reductions in emergence time may result in critical reductions in yield loss (Chapter 3). For example, oat emerging even 30 GDD earlier than wild oat would reduce yield loss from 33% to 28% at a wild oat density of 100 plants  $\text{m}^{-2}$ . In addition, although kernel weight and size were generally unaffected by wild oat time of emergence and density, wild oat contamination levels were well above the 1% limit allowed by milling industry (Quaker Oats Company of Canada, 2003). The current grade standards established by the oat milling industry allow 1% wild oat, 10% thin kernels, a minimum test weight of 47 kg/hl (Quaker Oats Company of Canada, 2003). Earlier emerging oat would have much reduced levels of wild oat contamination and thin kernels and may even meet many of the grading standards established by the milling industry. However, the genetic potential for early emergence in oat is currently not known and thus, selection for early emerging oat may be unsuccessful. Furthermore, since selections in oat breeding programs are generally made in weed-free plots, the results of selecting for earlier emergence will remain largely unknown with respect to competitive ability.

However, there may be agronomic opportunities for encouraging early emergence in oat. Seedbed quality, residue cover, and planting depth are important factors in maximizing the germination and emergence of annual crops (Lafond and Fowler, 1989; Chastain et al., 1995; Gan and Stobbe, 1995; Sidiras et al., 2000). Decreasing planting depth of oat seed may facilitate earlier emergence and thereby reduce losses caused by wild oat competition. In winter wheat, increasing planting depth from 19 to 76 mm increased median emergence time by 4.4 to 9.6 d depending on planting date (Lafond and Fowler, 1989). Given an average temperature in May of 11°C (Table 3.2), this would correspond to approximately 44 to 99 GDD, which, based on the results of this study, could lower yield loss by as much as 30% at a wild oat density of 50 plants  $\text{m}^{-2}$ . Gan and Stobbe (1995) suggested that shallow seed placement of less than 50 mm will maximize hard red spring wheat grain yield. Appropriate tillage and sowing techniques can also facilitate earlier emergence through reductions in soil factors that impede seedling

emergence such as soil crusting, improved seed placement, and better seed to soil contact (Stockton et al., 1996; Sidiras et al., 2000). Seedling emergence of barley in no-tillage plots was greater than in both rotary-hoed (minimum tillage) and ploughed (conventional tillage) (Sidiras et al., 2000). This was attributed to greater moisture contents and reduced penetration resistance of the soil under no-tillage cropping systems. Cultivation prior to seeding also resulted in lower soil moisture and a soft seedbed that increased the variance of planting depth resulting in poor winter wheat establishment (Stockton et al., 1996). Although no-tillage systems are associated with an increase in crop residue cover, higher seedbed residues did not affect either winter barley or winter wheat emergence (Chastain et al., 1995; McMaster et al., 2002). Oat producers should therefore avoid tillage to control early emerging wild oat as not only will delayed planting cause reduced yield and quality (May et al., 2004), the tillage operation itself may cause poor oat emergence resulting in reduced competitive ability with later emerging wild oat, further reducing yield and quality.

## **5.2 Oat caryopsis size and genotype**

Results presented in this thesis confirm previous reports indicating competitive differences among seed size in other crops. Oat plants established from large caryopses produced greater biomass and panicles per square meter than plants established from small caryopses, regardless of genotype or competition from wild oat (Chapter 4). Furthermore, wild oat biomass was substantially reduced when competing with plants derived from large seed. These findings lead us to accept the main hypothesis that planting large caryopses of more competitive genotypes may improve the competitive response of oat to wild oat competition, and agree with Stougaard and Xue (2004) whose results indicated that planting large wheat seed reduced yield losses incurred from wild oat competition. Moreover, they found that yield was increased more by planting large seed than by increasing seeding rates from 175 to 280 plants m<sup>-2</sup>. However, the results obtained in this study contrast those of Mian and Nafziger (1992) and Dhillon and Kler (1976) who reported that yields were not affected or were reduced by planting large seed.

Interestingly, the effect of seed size was generally consistent among all the varieties evaluated, and the lack of interaction observed indicates caryopsis size influences on oat competitive ability are not genotype-dependent. This suggests oat caryopsis size may be of great importance to competitive ability and thus, refutes my hypothesis that the effects of caryopsis size would be genotype-dependent. Nonetheless, biomass, tillering, and seed production differed among genotype. CDC Boyer had higher biomass and tillering than either of the other genotypes examined, irrespective of caryopsis size and wild oat competition (Table 4.3). Because of the high degree of correlation between biomass and seed production (Cousens and Mortimer, 1995), it is expected that CDC Boyer would also have yielded more than the other genotypes. This demonstrates an increased competitive ability of CDC Boyer versus the other genotypes examined in this study. Varietal differences in competitive ability with weeds have been reported in western Canadian (O'Donovan et al, 2000), European (Didon, 2002), and Australian (Lemerle et al., 1996) barley varieties.

In this study, my initial belief was that any differences observed between caryopsis size and variety may be attributed to earlier emergence or a higher leaf appearance rate. Surprisingly, no differences observed in either were related to caryopsis size or variety, contrasting the results of other studies (Grieve and Francois, 1992; Kaufmann, 1967; Lafond and Baker, 1986a; Stougaard and Xue, 2004). However, to the best of my knowledge, this is the first seed size study in a hulled species to account for differences in hull proportion, ensuring equal initial seed reserves among caryopsis sizes. Thus, the effect of genotype was essentially eliminated as genotypes were normalized for caryopsis size. This, as well as optimal growth conditions, likely contributed to the lack of differences observed in this study.

Plant competition experiments conducted under greenhouse conditions undoubtedly have conspicuous limitations with respect to extrapolation of results to field situations. The merits of greenhouse studies are commonly overshadowed by the question of what circumstances in nature, if any, they represent. However, it is critical to understand the objective of these (and my) studies is not to mimic natural conditions, but rather to provide the conditions necessary to investigate the dynamic nature of plant growth as



affected by various factors. Through this study, I was able to determine the potential of oat caryopsis size to affect oat – wild oat competition practically under greenhouse conditions as compared to a field study. Greenhouse studies provide a high degree of experimental control, repeatability, and precision when studying competitive interactions (Gibson et al., 1999). In addition to these attributes, because plant density was held constant among experimental units in this study, my results likely articulate true differences in oat competitive ability among caryopsis sizes. Nevertheless, low soil moisture or temperatures may produce different results under field conditions and therefore, the findings of this study should be interpreted with caution.

### **5.3 Management implications**

Several management recommendations regarding the use of alternative cultural methods to manage wild oat – oat competition can be derived from this study. Taken together, these recommendations will enable a more integrated approach to managing wild oat in oat by improving oat competitiveness with wild oat as well as suppressing wild oat growth. Nevertheless, control of wild oat in oat will remain arduous.

Clearly it is essential that growers try to avoid planting oat on wild oat infested fields as losses can be substantial (Chapter 3). In fields with a history of wild oat infestation, oat should be preceded with a competitive crop in which wild oat would be readily controlled if chem-fallow is not an option. Examples would include wheat, a crop in which many in-crop herbicides are highly effective in controlling wild oat, herbicide-tolerant canola, a short-term alfalfa crop, or even a silage crop such as barley. These crops would essentially reduce potential wild oat seed return and reduce wild oat infestations in the following oat crop. Nevertheless, it is evident that control measures must be taken to reduce the competitive effects of wild oat.

Wild oat that emerged before the crop caused reductions in yield as great as 70% and wild oat contamination of 15%. By ensuring that wild oat emergence occurs subsequent to crop emergence, it may be possible to reduce the negative effects of wild oat

competition on oat growth, yield, and quality. One way to ensure this is to apply a preemergence burnoff just prior to planting with a non-selective herbicide in order to provide the crop with the initial competitive advantage. This should allow the crop to emerge before any weeds as emerged weeds should have been controlled by the glyphosate burnoff. Considering the 5-year average oat price of \$1.85/bu and a yield loss of 21 bu/ac., even wild oat densities of 20 plants m<sup>-2</sup> emerging at the same time as oats would result in a loss of \$38.85/ac. Clearly, a \$3.20 per acre glyphosate application (Anonymous, 2003) is well warranted.

Although yield loss from later emerging wild oat was lower than from early emerging wild oat, the losses from later emerging wild oat were still substantial. When wild oat emerges subsequent to the crop, the only control is to destroy the crop and reseed. However, delayed seeding of oat results in reduced yield and quality (May et al., 2004). Therefore, producers must carefully assess wild oat populations before implementing a management strategy. The results of this study should be combined with those from previous field emergence studies to produce a decision-rules based model that will serve as a management guide for managing wild oat in oat based on density and time of emergence. With the application of this simple model, producers will be able to determine the yield loss caused by wild oat based on their relative time of emergence and oat seeding date, as well as wild oat density.

The effects of wild oat time of emergence and density on oat kernel weight and size were small and of little consequence. However, wild oat contamination levels at wild oat densities greater than 80 plants m<sup>-2</sup> were well above those tolerated by the milling industry. In addition to ensuring that wild oat emergence follows crop emergence, another strategy to prevent this would be to delay harvest, allowing wild oat to shed its seed prior to oat harvest thus keeping contamination low. However, consideration needs to be given to wild oat seedbank inputs with this strategy, as seedbank inputs would be high. This would be problematic due to the dormancy mechanism possessed by wild oat. Furthermore, it is currently not known whether delaying harvest affects oat yield and quality. Where wild oat seed production is anticipated to be high regardless of delayed

planting or harvesting, chaff collection at harvest should reduce wild oat seed return to the seedbank.

The ability of caryopsis size to improve the competitive response (the ability of a crop to tolerate weed competition) of oat to wild oat competition is encouraging. The differential competitiveness of oat seed of varying caryopsis sizes indicates that growers should consider varietal competitiveness with wild oat when choosing a variety to grow. This represents one low cost option in an integrated approach to wild oat management in oat. Furthermore, competitive response is often correlated with competitive effect (the ability of the crop to suppress the weed) and more importantly with yield under competition (Mohler, 2001a). Although grain yield was not measured in this study, large reductions in wild oat biomass and estimated fecundity occurred when competing with plants derived from large caryopses (Table 4.3). This emphasizes the importance of planting large seed when competition from wild oat is anticipated. The small seed used in this study are normally removed when screening for plump seed (passed through a 2.15- by 8.33 mm slotted sieve) and thus, by ensuring seed is screened prior to planting, some degree of wild oat control should be achieved. The results also indicate that planting plump seed of competitive cultivars could result in improvements in oat biomass and tillering, regardless of weed competition. Although further investigation is needed to examine the response of wild oat – oat competition to oat caryopsis size and genotype under field conditions, I predict that the results observed in this study would be enhanced under field conditions due to environmental heterogeneity. It is likely that the ability of large-seeded materials to preempt belowground resources would be very important under the moisture-limited conditions frequently experienced in the Northern Great Plains region.

#### **5.4 Future research**

This research has provided a quantification of oat yield and quality losses due to wild oat time of emergence and density. However, these results are based on a study conducted at only one crop density. The incorporation of several crop densities into a

study would allow the construction of a significantly more precise and inclusive empirical model to describe crop yield loss. Nonetheless, the results of this study will prove useful in the development of a model to aid growers in decision-making regarding wild oat management in oat. Although critical to successful wild oat management in oat, such a model remains to be constructed.

Empirical models such as those used in this study are ultimately limited in their ability to provide accurate parameter estimates due to year and location variability. Although the models I used accurately describe the data to which they were fit, coefficient instability led to separate models being fit for each site-year. This reduces the predictive power of the model as well as its applicability. Coefficient instability likely results from a number of factors, most of which would be regarded as random rather than fixed effects in the model. Nonetheless, current empirical models such as those described by Cousens et al. (1987) use nonlinear regression and treat years and locations inappropriately as fixed effects. Nonlinear mixed-model regression provides a way to treat years and locations as random effects and as such, may circumvent the problem of coefficient instability in empirical models, providing more robust and precise parameter estimates. Nielsen et al. (2004) have recently described a novel nonlinear mixed-model regression procedure which incorporates random effects into a nonlinear model. It would be worthwhile to test this procedure on empirical models such as those used in this study including years and locations as random effects in an effort to provide more precise, biologically meaningful parameter estimates. I believe that this process may allow a common model to be fit to data from all site-years.

This is the first study to plant and analyze based on thermal time and as such, comparisons of results presented in this thesis to previous studies remain limited. That said, comparisons to O'Donovan et al. (1985) and Cousens et al. (1987) revealed that oat may be similar to or more competitive with wild oat than either wheat or barley. This information would be useful particularly to organic growers and therefore these observations may warrant an investigation comparing the competitive abilities of wheat, barley, and oat with wild oat in a replacement series study.

The greenhouse study has also generated some important questions worthy of attention. Surprisingly, no differences in emergence time among various oat caryopsis sizes or varieties were observed in this study. Although I speculated that this might be due to the optimal conditions under which germination and emergence occurred, no published information exists regarding germination or emergence of oat under various stresses. Thus, germination and emergence studies should be conducted on oat varying for caryopsis size and variety to determine if differences exist under stressed conditions that could then become advantageous under field conditions.

This study could not clearly elucidate differences in early seedling vigor among oat sizes or genotypes. Laboratory or field studies examining the response of various size classes and varieties to cold temperature and deep seeding may prove beneficial in determining variation in early season vigor and canopy establishment among oat seed sizes and varieties. Furthermore, this study was conducted under greenhouse conditions and although the results are promising, field studies are needed to confirm results before further recommendations can be made.

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